IAEA International Atomic Energy Agency

IAEA webinar on 1 September, 2022

New Tools of Phantoms, Monte Carlo Person-Specific Organ Dosimetry in Radiation Protection: Do We Have the Necessary Computational Tools for a Paradigm Change?

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And
Dept of Radiation Oncology, First Affiliated Hospital
University of Science and Technology of China
Hefei, China
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Disclosures:

Developer of commercial software tools:

By Virtual Phantoms
https://www.virtual-dose.com

DeepViewer

By Wisdom Tech http://www.wisdom-tech.online/

Learning objectives:

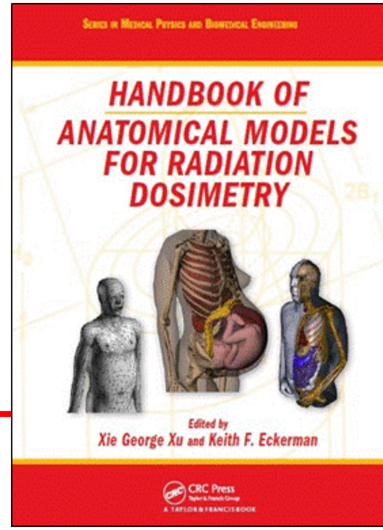
1. **To gain a historical perspective of computational human phantoms and Monte Carlo dose calculations;**

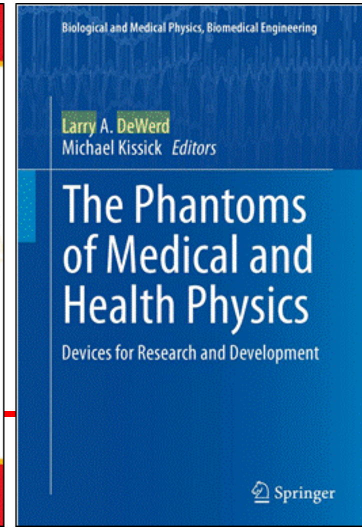
2. **To learn about the latest research and development on patient-specific phantoms involving automatic multi-organ segmentation tools;**

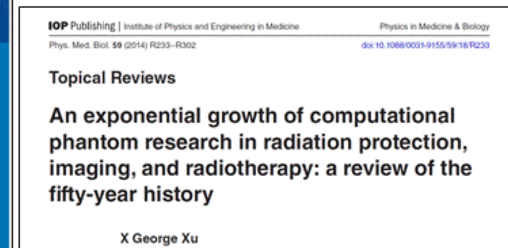
3. **To learn about the latest research and development on rapid Monte Carlo dose calculation tools involving GPU co-processors as well as virtual-source-modeling of CT and PET/CT scanner, radiotherapy linac, and those found in common radiation protection environments.**

60-Year History of Computational Phantoms

- Radiation Protection
- Medical Imaging
- Radiotherapy



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Phys. Med. Biol. 59 (2014) R233–R302 | doi:10.1088/0031-9155/59/18/R233

Topical Reviews

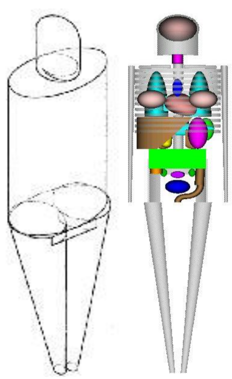
An exponential growth of computational phantom research in radiation protection, imaging, and radiotherapy: a review of the fifty-year history

X George Xu

1st Generation
STYLIZED

2nd Generation
VOXEL

3rd Generation
BREP



ORNL family models
1960-1980s

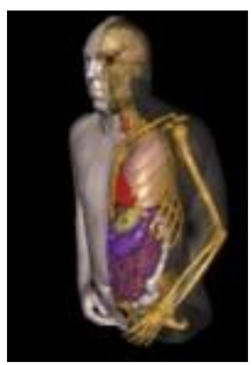
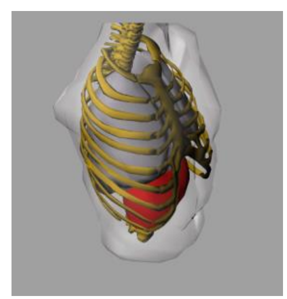


Image-based
1980s-present



Deformable 4D models
2000s-present

- Personalization
- Multi-scale (voxel – DNA)

Comments

- **For decades, in imaging procedures, all "organ doses" were assessed using ICRP "Reference Man" approach involving "population-averaged phantom libraries"**
- **"Patient-specific organ doses" would require two newly available tools:**
  1. **automatic organ segmentation**
  2. **"near real-time" Monte Carlo simulations**

Outline of the presentation

Anatomical Modeling Tool

Dose Reporting Tool

VirtualDose

Organ Segmentation Tool

Deep Viewer

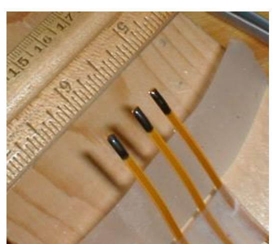
Dose Computing Tool

ARCHER

Two Ways to Determine Organ Doses

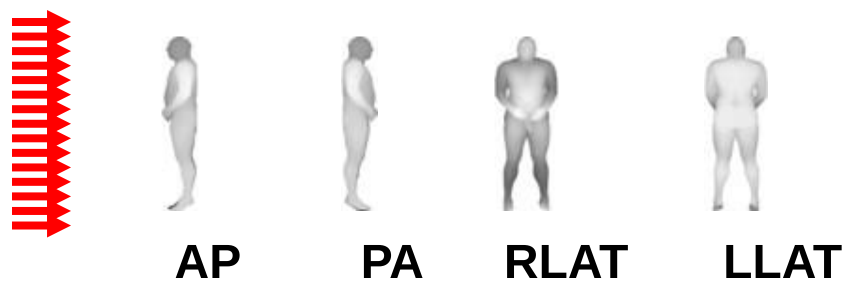
Measurements

- Dosimeters
- Physical phantom



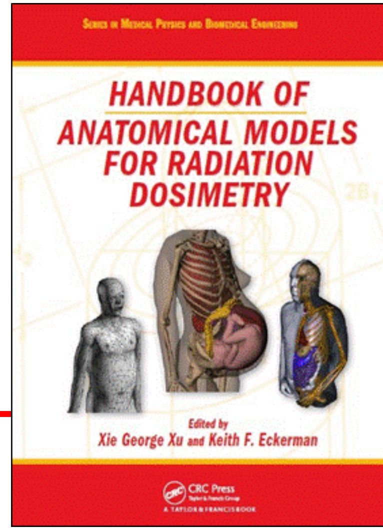
Monte Carlo Simulations

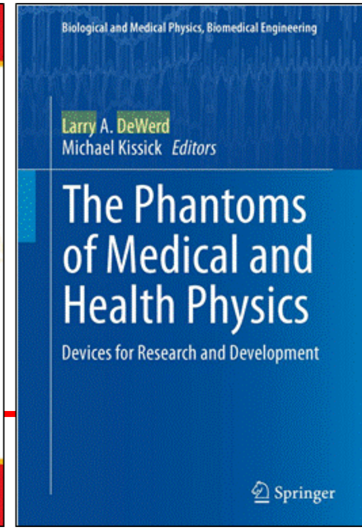
- Computational phantoms
- Monte Carlo codes

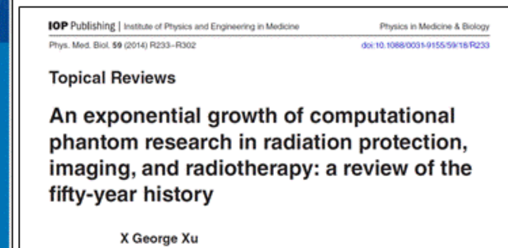


60-Year History of Computational Phantoms

- Radiation Protection
- Medical Imaging
- Radiotherapy



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Topical Reviews

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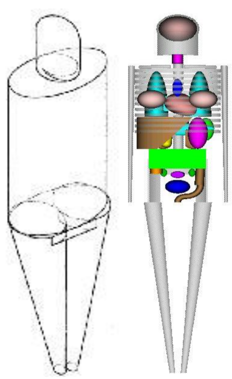
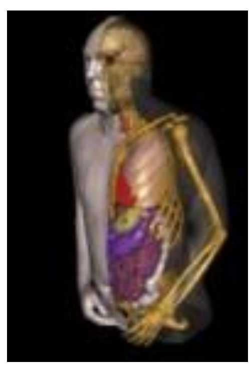
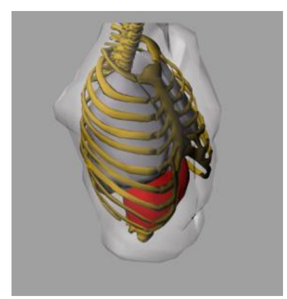






- Personalization
- Multi-scale (voxel – DNA)

ORNL family models
1960-1980s

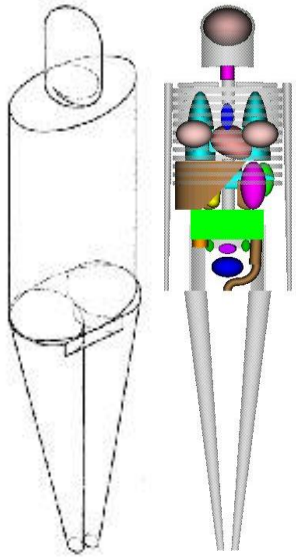
Image-based
1980s-present

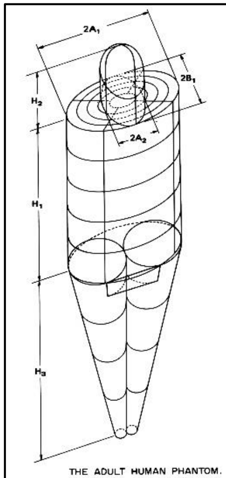
Deformable 4D models
2000s-present

1st-Generation "Stylized" Phantoms

(Society of Nuclear Medicine's MIRD Committee)

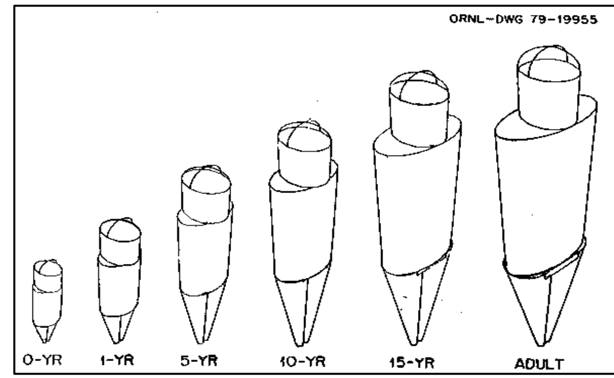
- *ICRP paradigm based on "population averaged" Reference Man concept*
- *Anatomically simple and friendly for computers prior to 1980s*



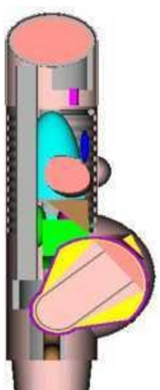


PHANTOM DIMENSIONS AND DOSE REGIONS

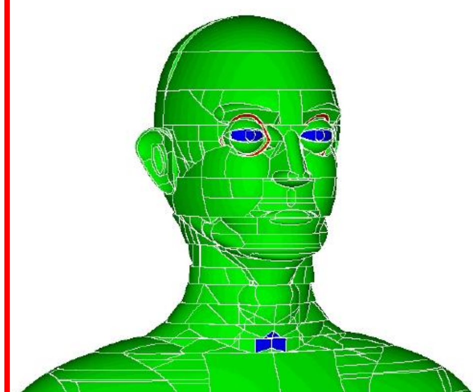
Age (yr)	Weight (kg)	H_1 (cm)	H_2 (cm)	H_3 (cm)	A_1 (cm)	B_1 (cm)	A_2 (cm)
0	3.148	23	13	16	5.5	5	4.5
1	9.112	33	16	28.8	8	7	6.5
5	18.12	45	20	46	11	7.5	6.5
10	30.57	54	22	64	14	8	6.5
15	53.95	65	23	78	18	9	7
Adult	69.88	70	24	80	20	10	7



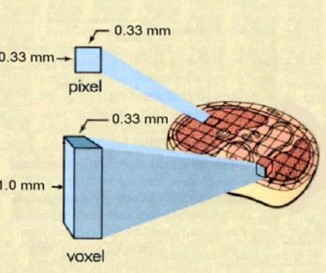
Snyder *et al* (1978), Cristy (1980), and Cristy and Eckerman (1987), plus ADAM/Eva phantoms by Kramer et al (1982) from Germany



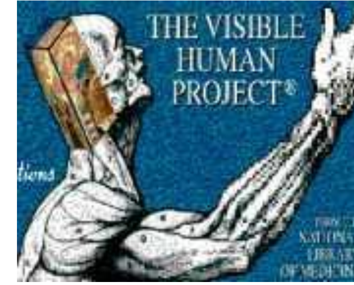
At the end of each trimester of pregnancy (**Stabin *et al* 1995**)



- The Computational Anatomical Man (CAM) and
- CAF (Computerized Anatomical Female)
- by **Billings and Yucker (1973)**
- Used exclusively by NASA

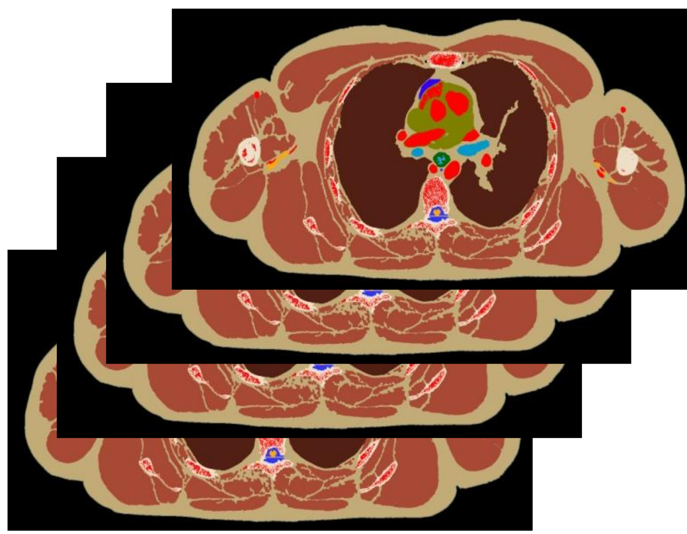


2nd-Generation "Voxel" Phantoms - Example of the VIP-Man (1997-2000)

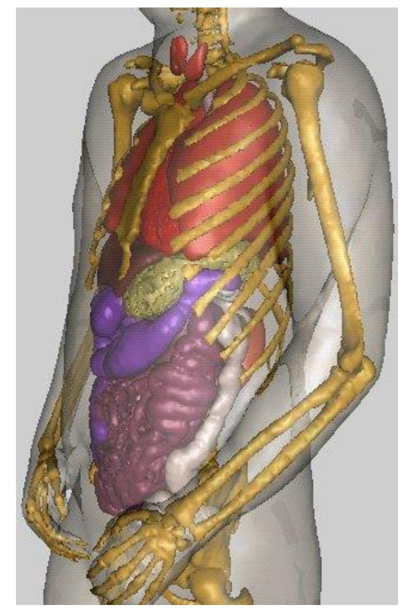


Xu XG, Chao TC, Bozkurt A. VIP-Man: An image-based whole-body adult male model constructed from color photographs of the Visible Human Project for multi-particle Monte Carlo calculations. Health Phys., 78(5):476-486, 2000. ***One of the most cited (450+)***

Identification of organs in each slice of a 2D pixel map



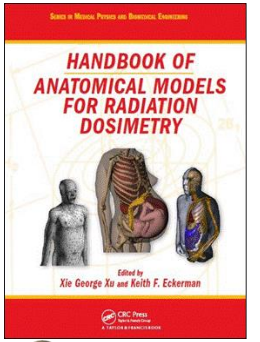
Registration of all slices



Finished 3D voxel VIP-Man

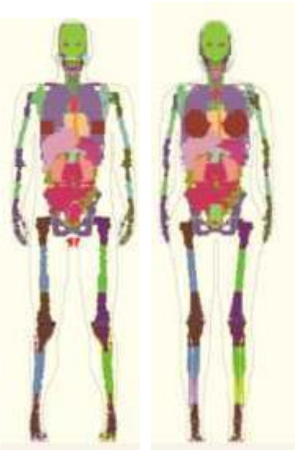
<<Handbook of Anatomical Models for Radiation Dosimetry>> by Xu and Eckerman 2009

– curtsey images



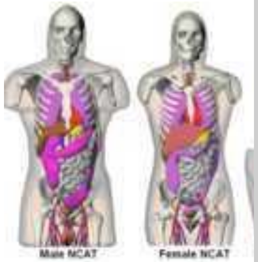
REX & REGINA (ICRP)

NORMAN

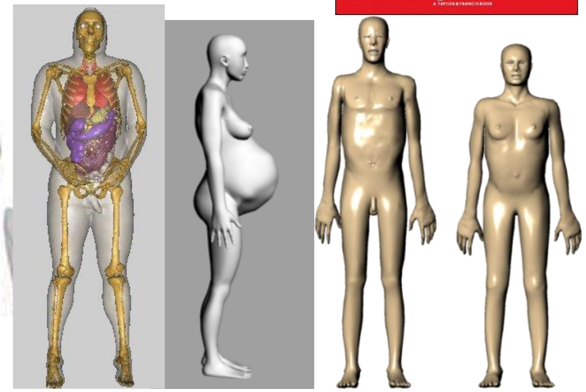


MAX06 FAX06

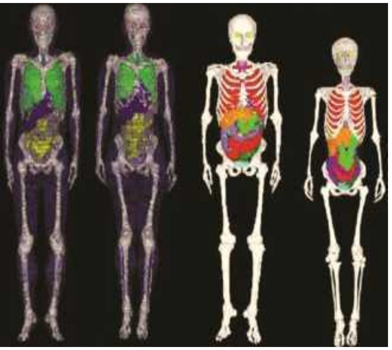
Zubal



NCAT

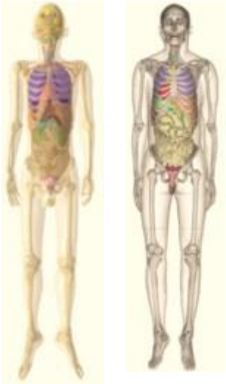


VIP-Man, Pregnant, Adult M/F

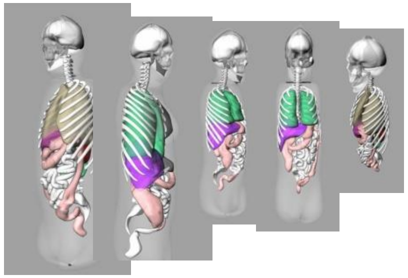


Otoko Onago JM KF

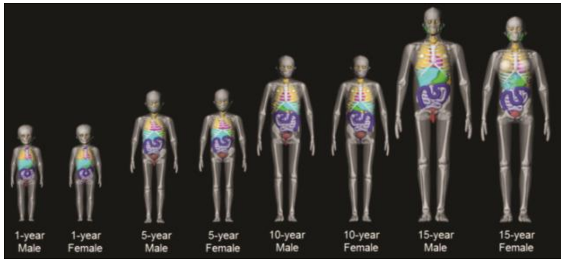
KTMAN 1, 2



CNMAN VCH



Vanderbilt Family



UF Family

3rd-Generation "BREP" Phantoms (NURBS or Meshes)

Pregnant Phantoms

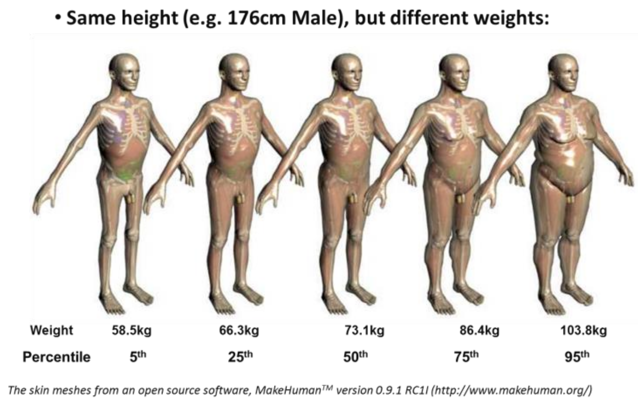
Xu X G, Taranenko V, Zhang J, Shi C. A boundary-representation method for designing whole-body radiation dosimetry models: pregnant females representing three gestational periods, RPI-P3, -P6 and –P9. Phys. Med. Biol. (2007)

The Best 10 papers by PBM in 2007

9-month 6-month 3-month

Size and Weight Adjustable Phantoms

Na YH, Zhang* B, Zhang* J, Caracappa PF, Xu XG. Deformable Adult Human Phantoms for Radiation Protection Dosimetry: Anatomical Data for Covering 5th- 95th Percentiles of the Population and Software Algorithms. Phys. Med. Biol. 55: 3789-3811 (2010).

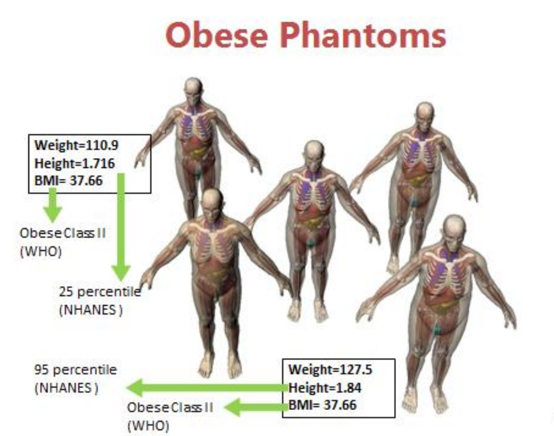


Obese Individuals

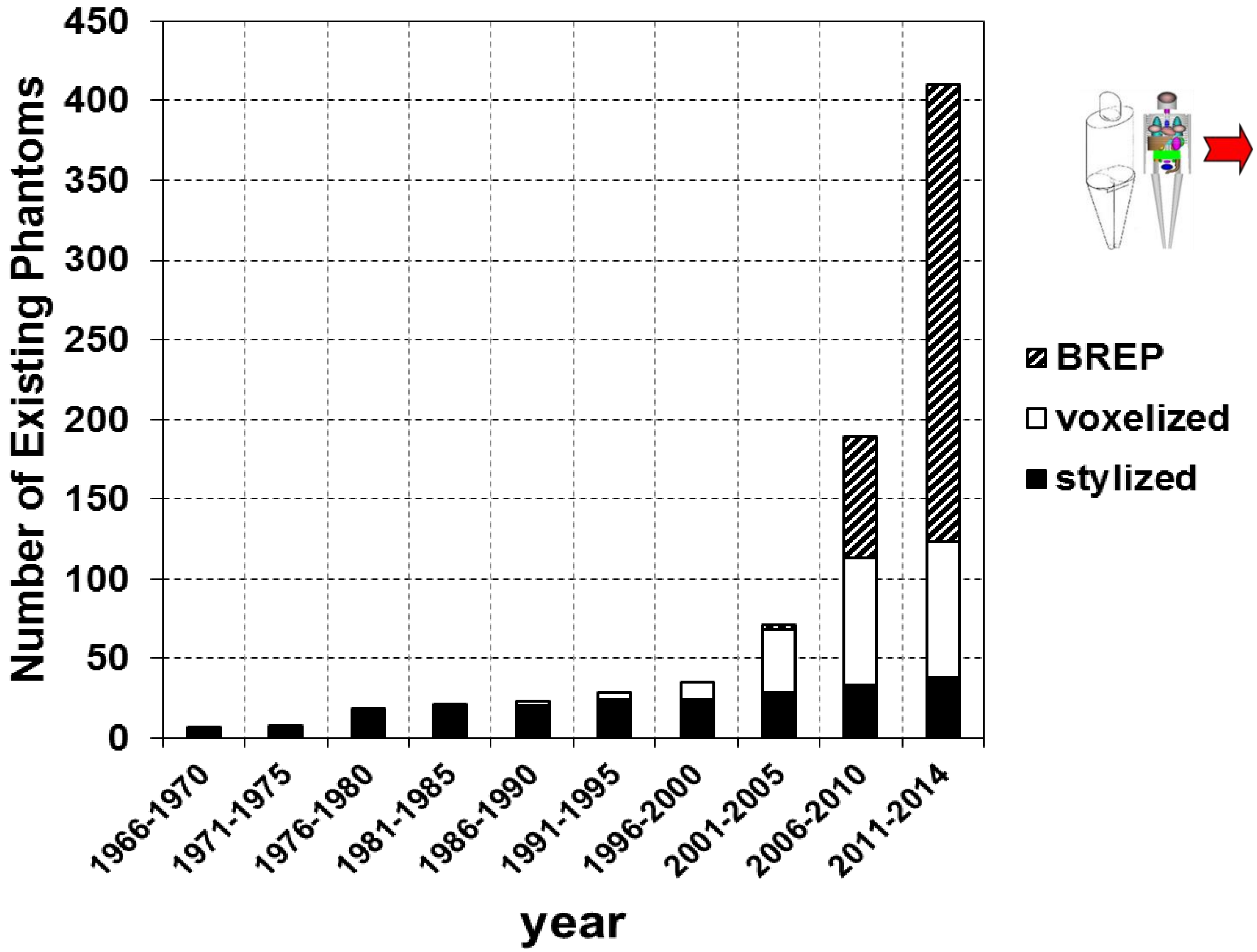
Ding A, Mille MM, Liu T, Caracappa PF and Xu XG. Phys. Med. Biol. 57:2441–2459 (2012).

One of the most downloaded in 2012

Weight Category	BMI
Underweight	< 18.5
Normal Weight	18.5-24.9
Overweight	25-29.9
Obese (I, II)	30-34.9, 34.9-39.9
Morbidly Obese	>40

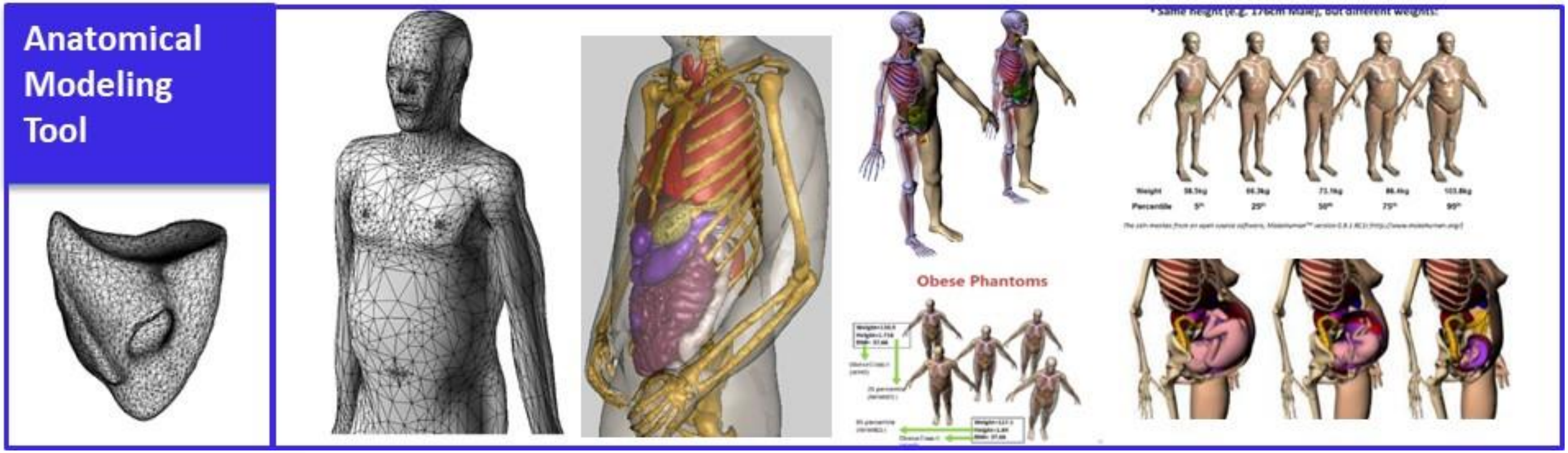


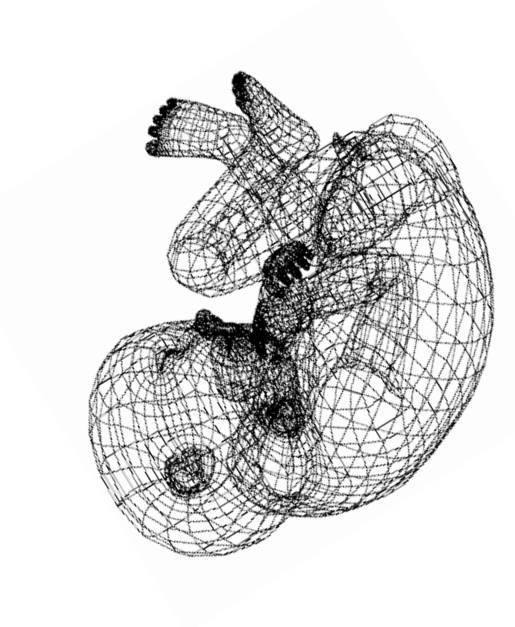
The number of phantoms in existence since 1966 shows a surprising exponential growth

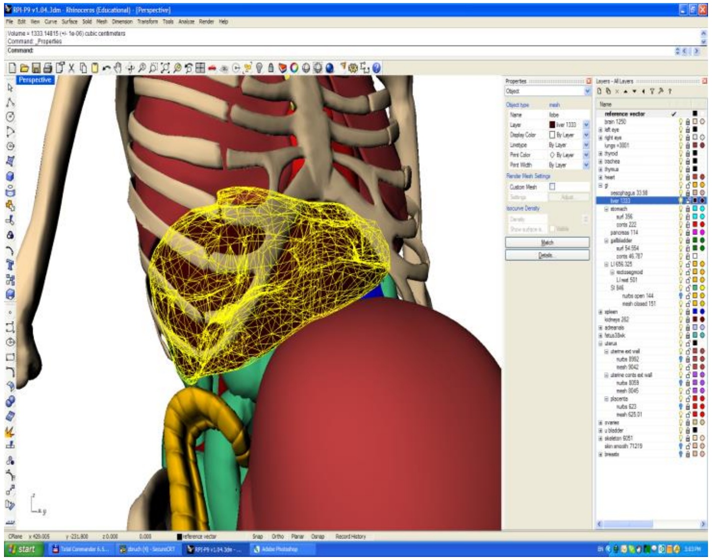


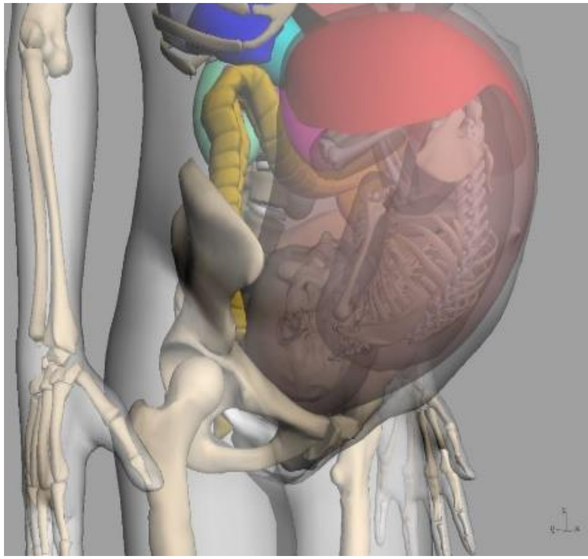
X. George Xu, "An exponential growth of computational phantom research in radiation protection, imaging, and radiotherapy: a review of the fifty-year history," Physics in Medicine & Biology, 59(R233-R302) 2014.

Voxel mesh geometric modeling tools

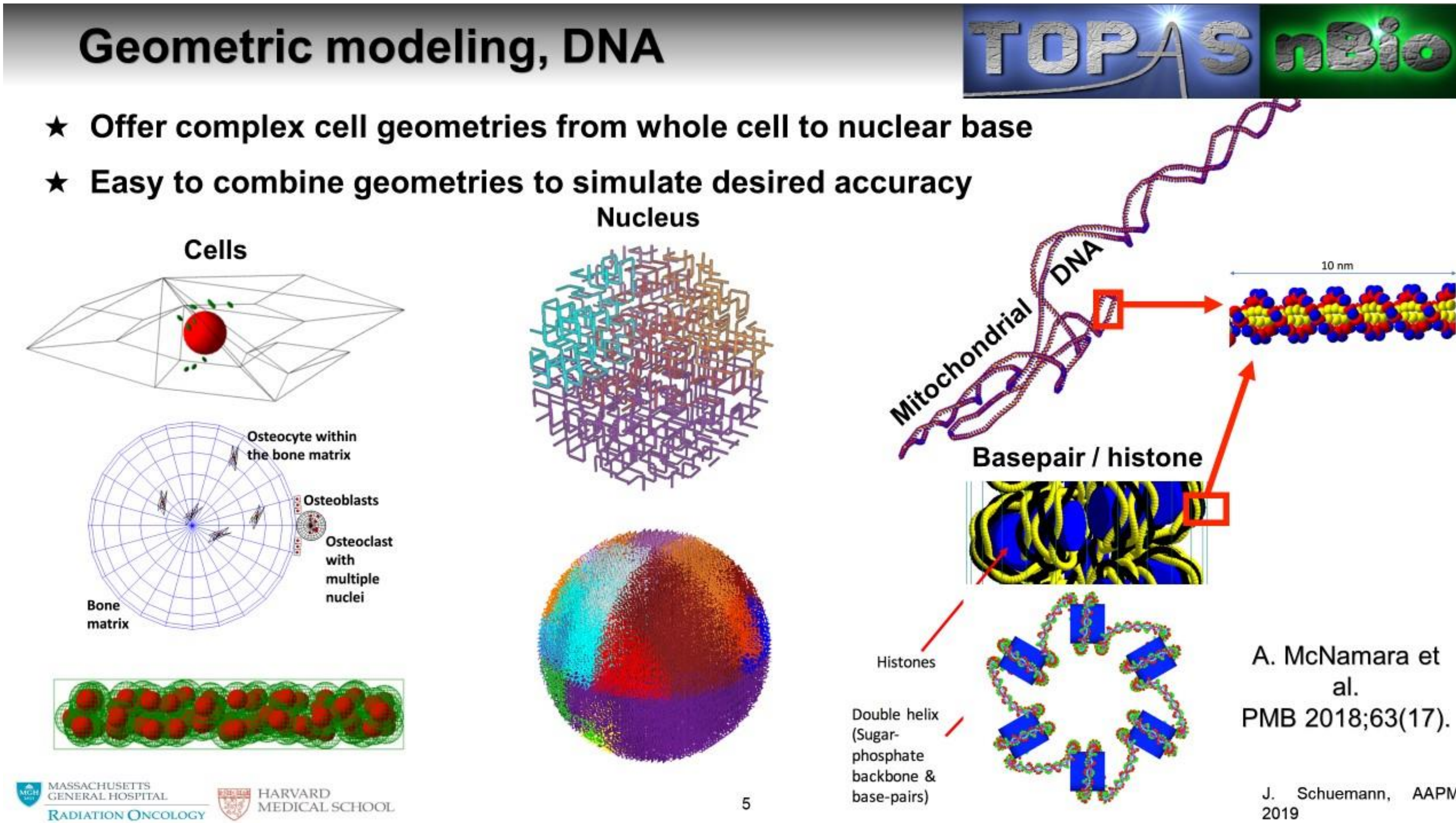








Future Radiobiological Predictive Modeling at Multi-Scale - To Bridge the Gap Between Voxel and DNA



Courtesy slide from Jan Schuemann

Outline of the presentation

Anatomical Modeling Tool

Dose Reporting Tool

VirtualDose

Organ Segmentation Tool

Deep Viewer

Dose Computing Tool

ARCHER

Cancer risks of pediatrics from CT
by Pearce, et al. Lancet 2012

- 178,604 young patients
- CT scans from 1985 -2002
- 81 hospitals in Great Britain
- Cancer data from 1985 - 2008

	Male patients		**Female patients**	
	Brain dose (mGy)	Red bone marrow dose (mGy)	Brain dose (mGy)	Red bone marrow dose (mGy)
Age at brain CT				
0 years	28	8	28	8
5 years	28	9	28	9
10 years	35	6	35	6
15 years	43	4	44	6
20 years	35	2	42	2
Age at chest CT				
0 years	0·4	4	0·4	4
5 years	0·3	3	0·3	3
10 years	0·3	3	0·3	3
15 years	0·2	4	0·3	4
20 years	0·2	4	0·3	4
Age at abdominal CT				
0 years	0·2	3	0·2	3
5 years	0·1	2	0·1	2
10 years	0·1	3	0·1	3
15 years	0·0	3	0·0	3
20 years	0·0	3	0·0	4
Age at extremity CT				
0 years	0·0	1	0·0	1
5 years	0·0	0·2	0·0	0·2
10 years	0·0	0·1	0·0	0·1
15 years	0·0	0·0	0·0	0·0
20 years	0·0	0·0	0·0	0·0

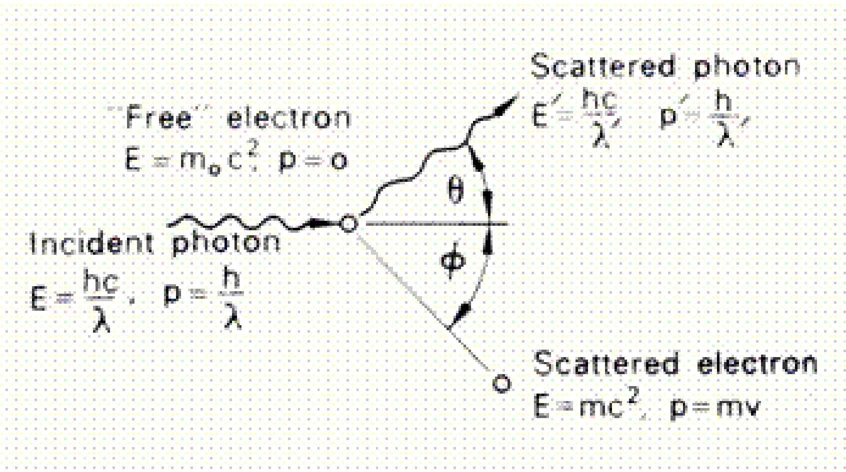
Table 1: Estimated radiation doses to the brain and red bone marrow from one CT scan, by scan type, sex, and age at scan, as used in this study for scans after 2001

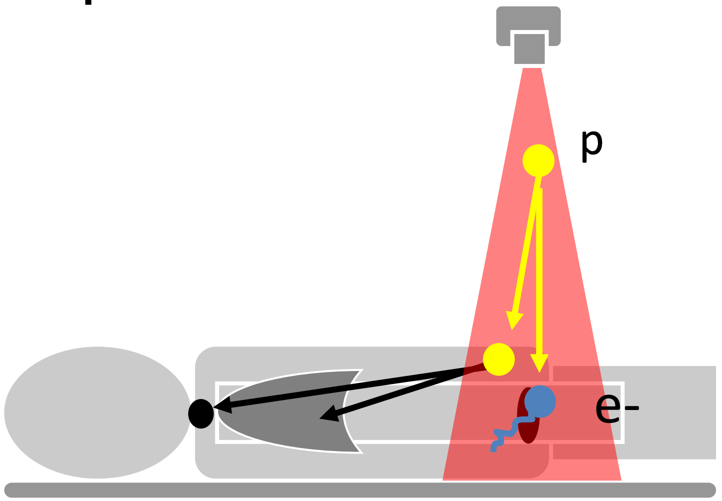
Radiation Physics for CT Scans

X-ray photon interactions (< 160 keV)

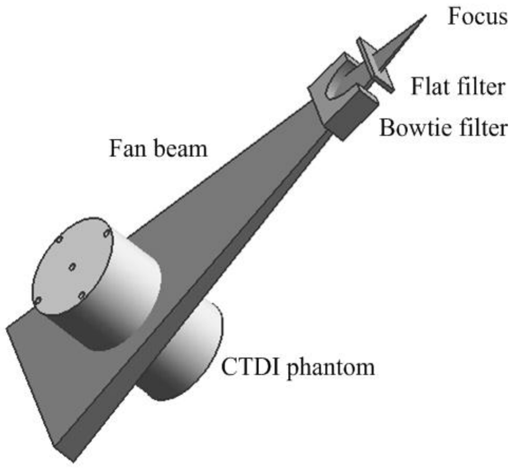
- ✓ **Photoelectric effect**
- ✓ **Compton scattering**

$$E_{pe} = hf - \phi$$

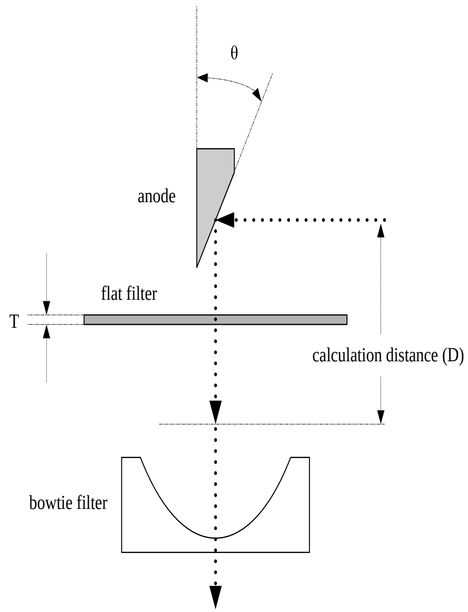




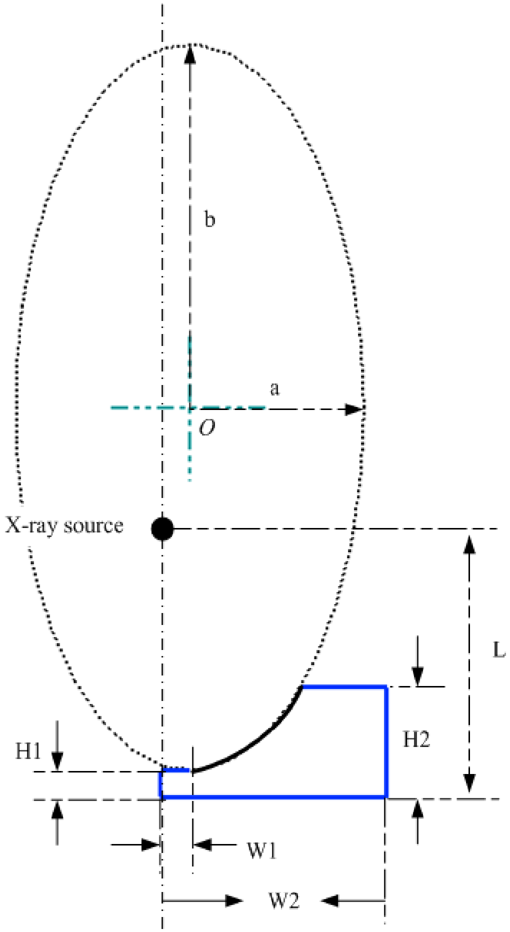
Method: Modeling methodology



(a)



(b)



(c)

Illustration of components of CT scan and modeling of CT scan, (a) components of the scan, (b) illustration of CT source model, (c). illustration of parameters for BTF (Gu et al. 2009)

A Comprehensive Slice-by-slice Organ Dose Database

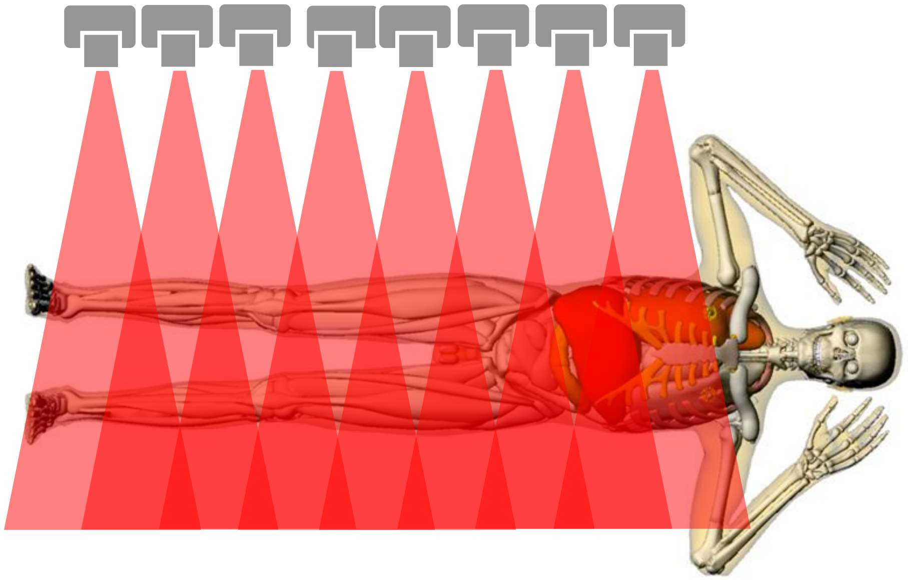
http://www.virtual-dose.com

- **Axial scan simulations in MCNPX**
- **Contiguous scans from the top to the bottom of 27 phantoms**
- CT technical parameters

  -4 different tube voltages: 80, 100, 120, and 140 kVp

  -4 different beam collimations: 1.25 mm, 5 mm , 10 mm and 20 mm

  -Using both the head and body bowtie filters

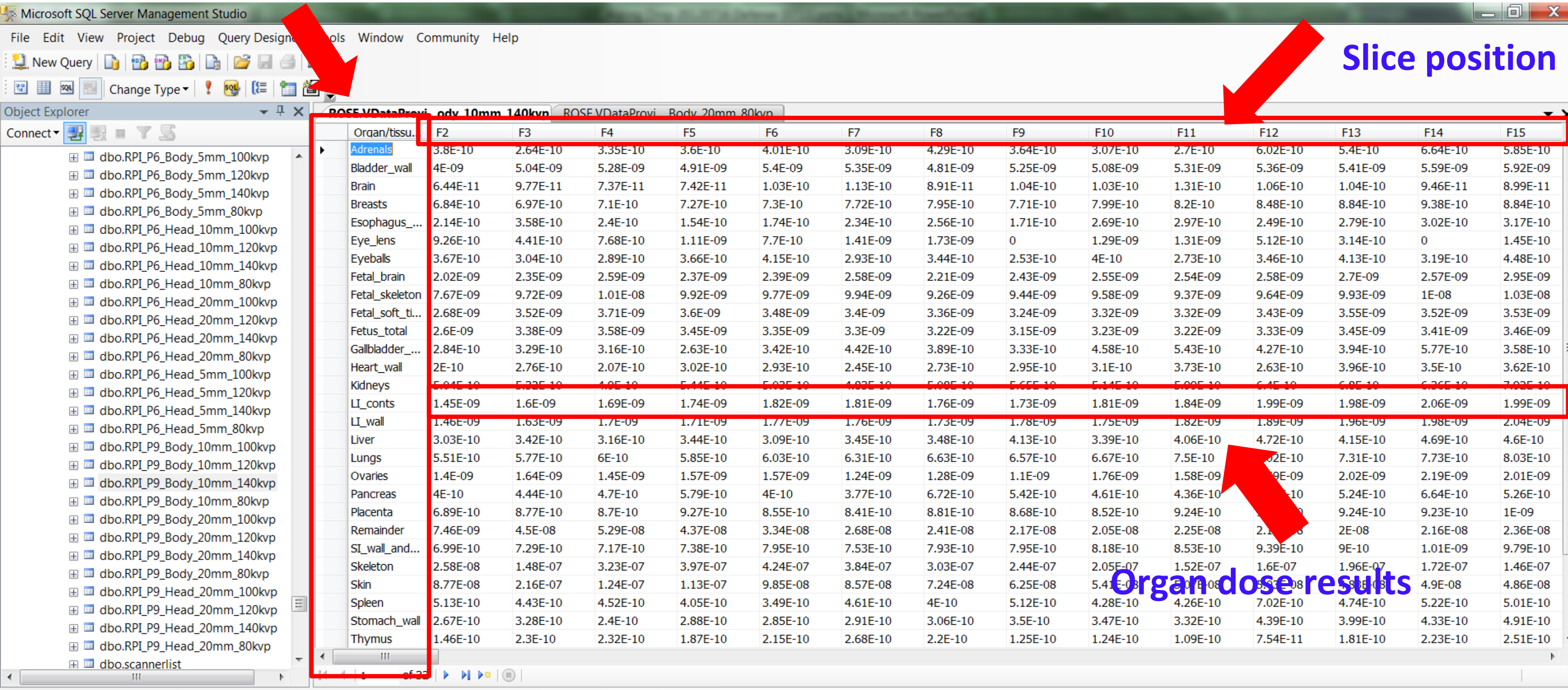


Database Hosted in SQL Data Server

http://www.virtual-dose.com

Organ name

Slice position



Organ/tissu...	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15
Adrenals	3.8E-10	2.64E-10	3.35E-10	3.6E-10	4.01E-10	3.09E-10	4.29E-10	3.64E-10	3.07E-10	2.7E-10	6.02E-10	5.4E-10	6.64E-10	5.85E-10
Bladder_wall	4E-09	5.04E-09	5.28E-09	4.91E-09	5.4E-09	5.35E-09	4.81E-09	5.25E-09	5.08E-09	5.31E-09	5.36E-09	5.41E-09	5.59E-09	5.92E-09
Brain	6.44E-11	9.77E-11	7.37E-11	7.42E-11	1.03E-10	1.13E-10	8.91E-11	1.04E-10	1.03E-10	1.31E-10	1.06E-10	1.04E-10	9.46E-11	8.99E-11
Breasts	6.84E-10	6.97E-10	7.1E-10	7.27E-10	7.3E-10	7.72E-10	7.95E-10	7.71E-10	7.99E-10	8.2E-10	8.48E-10	8.84E-10	9.38E-10	8.84E-10
Esophagus_...	2.14E-10	3.58E-10	2.4E-10	1.54E-10	1.74E-10	2.34E-10	2.56E-10	1.71E-10	2.69E-10	2.97E-10	2.49E-10	2.79E-10	3.02E-10	3.17E-10
Eye_lens	9.26E-10	4.41E-10	7.68E-10	1.11E-09	7.7E-10	1.41E-09	1.73E-09	0	1.29E-09	1.31E-09	5.12E-10	3.14E-10	0	1.45E-10
Eyeballs	3.67E-10	3.04E-10	2.89E-10	3.66E-10	4.15E-10	2.93E-10	3.44E-10	2.53E-10	4E-10	2.73E-10	3.46E-10	4.13E-10	3.19E-10	4.48E-10
Fetal_brain	2.02E-09	2.35E-09	2.59E-09	2.37E-09	2.39E-09	2.58E-09	2.21E-09	2.43E-09	2.55E-09	2.54E-09	2.58E-09	2.7E-09	2.57E-09	2.95E-09
Fetal_skeleton	7.67E-09	9.72E-09	1.01E-08	9.92E-09	9.77E-09	9.94E-09	9.26E-09	9.44E-09	9.58E-09	9.37E-09	9.64E-09	9.93E-09	1E-08	1.03E-08
Fetal_soft_ti...	2.68E-09	3.52E-09	3.71E-09	3.6E-09	3.48E-09	3.4E-09	3.36E-09	3.24E-09	3.32E-09	3.32E-09	3.43E-09	3.55E-09	3.52E-09	3.53E-09
Fetus_total	2.6E-09	3.38E-09	3.58E-09	3.45E-09	3.35E-09	3.3E-09	3.22E-09	3.15E-09	3.23E-09	3.22E-09	3.33E-09	3.45E-09	3.41E-09	3.46E-09
Gallbladder_...	2.84E-10	3.29E-10	3.16E-10	2.63E-10	3.42E-10	4.42E-10	3.89E-10	3.33E-10	4.58E-10	5.43E-10	4.27E-10	3.94E-10	5.77E-10	3.58E-10
Heart_wall	2E-10	2.76E-10	2.07E-10	3.02E-10	2.93E-10	2.45E-10	2.73E-10	2.95E-10	3.1E-10	3.73E-10	2.63E-10	3.96E-10	3.5E-10	3.62E-10
Kidneys	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
LI_conts	1.45E-09	1.6E-09	1.69E-09	1.74E-09	1.82E-09	1.81E-09	1.76E-09	1.73E-09	1.81E-09	1.84E-09	1.99E-09	1.98E-09	2.06E-09	1.99E-09
LI_wall	1.46E-09	1.63E-09	1.7E-09	1.71E-09	1.77E-09	1.76E-09	1.73E-09	1.78E-09	1.75E-09	1.82E-09	1.89E-09	1.96E-09	1.98E-09	2.04E-09
Liver	3.03E-10	3.42E-10	3.16E-10	3.44E-10	3.09E-10	3.45E-10	3.48E-10	4.13E-10	3.39E-10	4.06E-10	4.72E-10	4.15E-10	4.69E-10	4.6E-10
Lungs	5.51E-10	5.77E-10	6E-10	5.85E-10	6.03E-10	6.31E-10	6.63E-10	6.57E-10	6.67E-10	7.5E-10	[illegible]	7.31E-10	7.73E-10	8.03E-10
Ovaries	1.4E-09	1.64E-09	1.45E-09	1.57E-09	1.57E-09	1.24E-09	1.28E-09	1.1E-09	1.76E-09	1.58E-09	[illegible]	2.02E-09	2.19E-09	2.01E-09
Pancreas	4E-10	4.44E-10	4.7E-10	5.79E-10	4E-10	3.77E-10	6.72E-10	5.42E-10	4.61E-10	4.36E-10	[illegible]	5.24E-10	6.64E-10	5.26E-10
Placenta	6.89E-10	8.77E-10	8.7E-10	9.27E-10	8.55E-10	8.41E-10	8.81E-10	8.68E-10	8.52E-10	9.24E-10	[illegible]	9.24E-10	9.23E-10	1E-09
Remainder	7.46E-09	4.5E-08	5.29E-08	4.37E-08	3.34E-08	2.68E-08	2.41E-08	2.17E-08	2.05E-08	2.25E-08	[illegible]	2E-08	2.16E-08	2.36E-08
SI_wall_and...	6.99E-10	7.29E-10	7.17E-10	7.38E-10	7.95E-10	7.53E-10	7.93E-10	7.95E-10	8.18E-10	8.53E-10	9.39E-10	9E-10	1.01E-09	9.79E-10
Skeleton	2.58E-08	1.48E-07	3.23E-07	3.97E-07	4.24E-07	3.84E-07	3.03E-07	2.44E-07	2.05E-07	1.52E-07	1.6E-07	1.96E-07	1.72E-07	1.46E-07
Skin	8.77E-08	2.16E-07	1.24E-07	1.13E-07	9.85E-08	8.57E-08	7.24E-08	6.25E-08	[illegible]	[illegible]	[illegible]	[illegible]	4.9E-08	4.86E-08
Spleen	5.13E-10	4.43E-10	4.52E-10	4.05E-10	3.49E-10	4.61E-10	4E-10	5.12E-10	4.28E-10	4.26E-10	7.02E-10	4.74E-10	5.22E-10	5.01E-10
Stomach_wall	2.67E-10	3.28E-10	2.4E-10	2.88E-10	2.85E-10	2.91E-10	3.06E-10	3.5E-10	3.47E-10	3.32E-10	4.39E-10	3.99E-10	4.33E-10	4.91E-10
Thymus	1.46E-10	2.3E-10	2.32E-10	1.87E-10	2.15E-10	2.68E-10	2.2E-10	1.25E-10	1.24E-10	1.09E-10	7.54E-11	1.81E-10	2.23E-10	2.51E-10

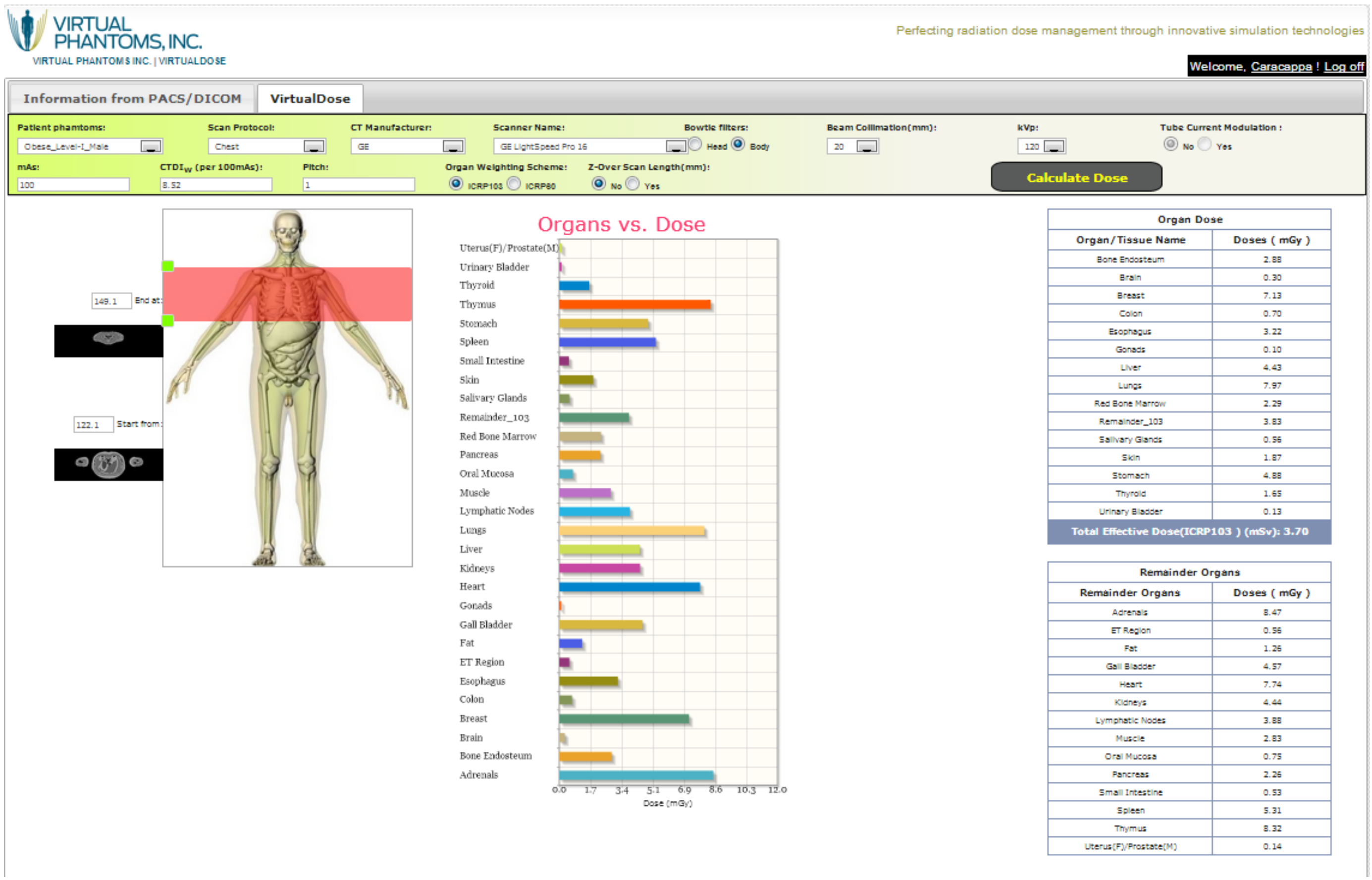
Organ dose results

Easy to manage and update

CT Dose Reporting Software

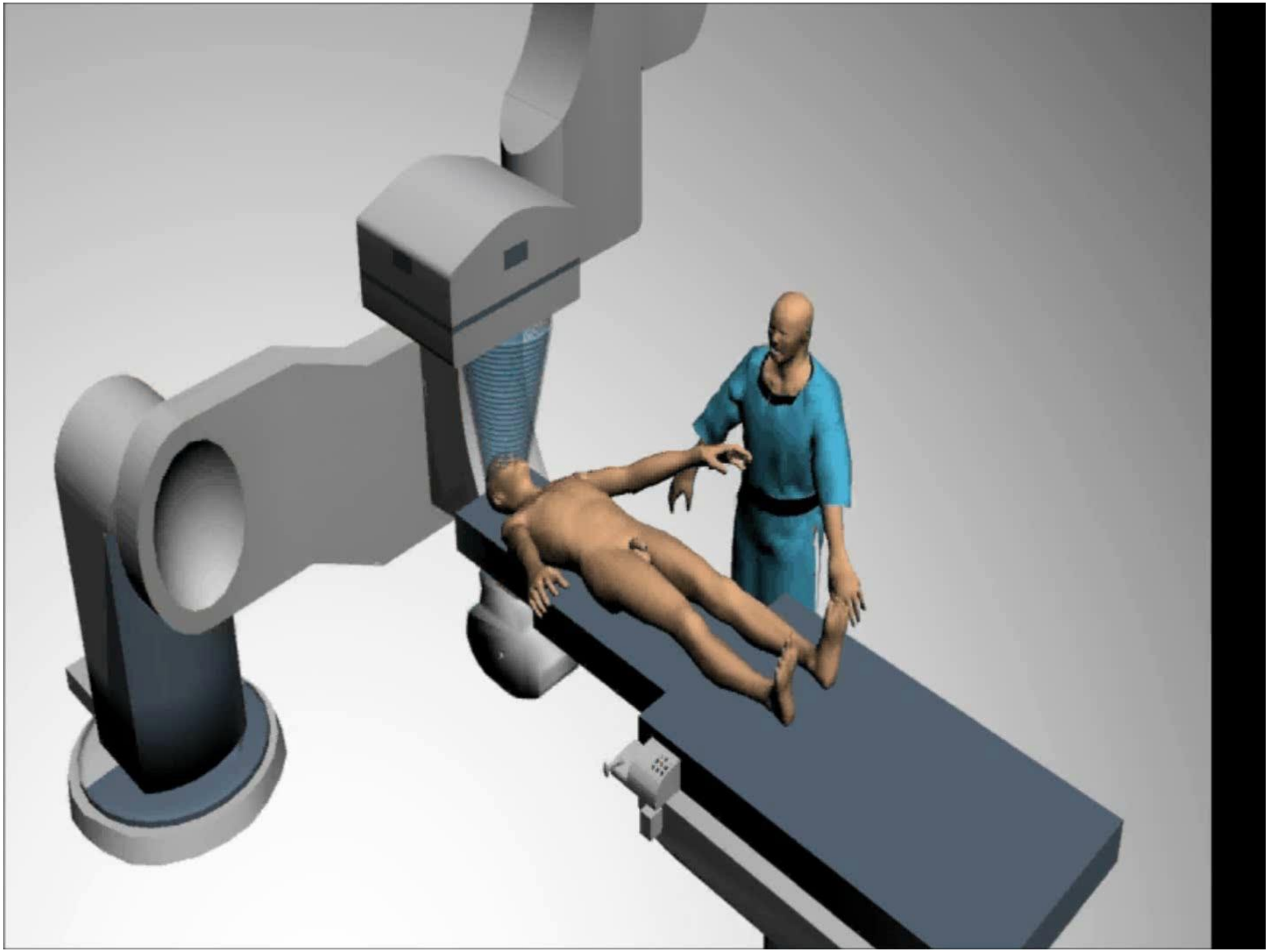
VirtualDose™ CT
A product of Virtual Phantoms, Inc.

http://www.virtual-dose.com



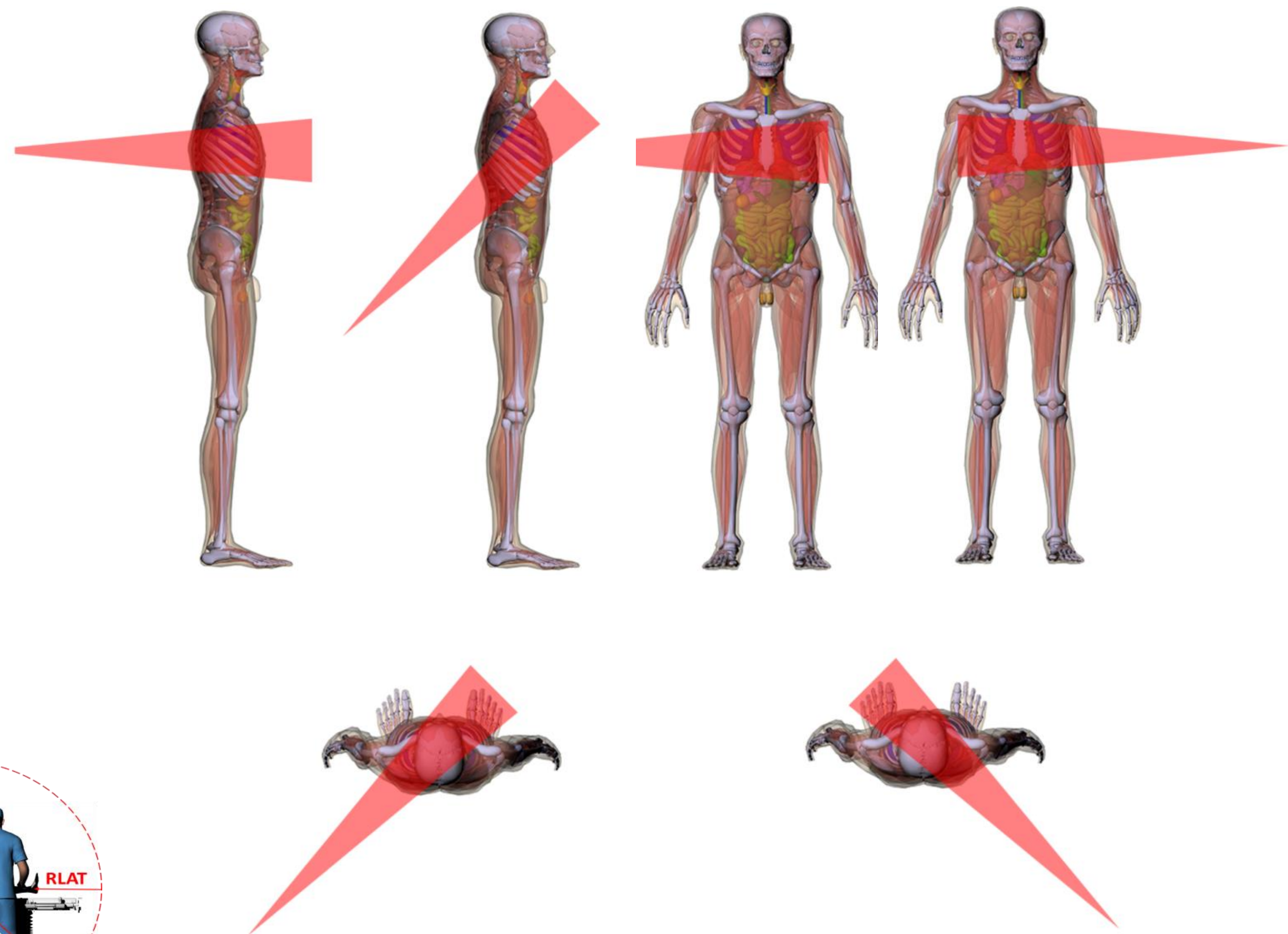
In 2021-2022, over <u>31.5-million</u> dose calculation requests from more than 275 sites worldwide were processed

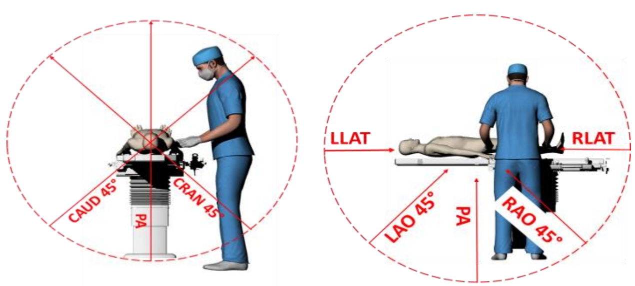
VirtualDose for Interventional Radiology



VirtualDose-IR
Dose from fluoroscopically guided intervention (FGI) - Patients

- **Simulated beam directions:**
  - **Posterior-Anterior, Crani 45 °**
  - **Lateral: left & right**
  - **Oblique: 45° left & right**



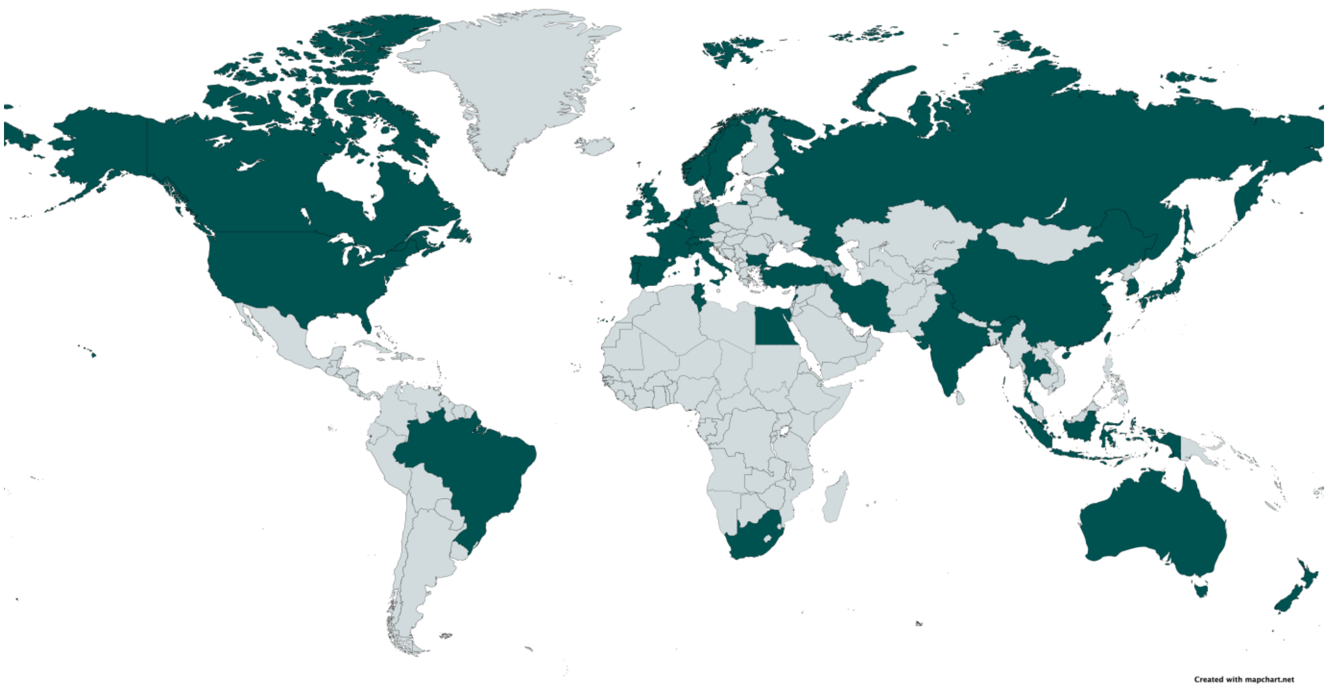


VIRTUAL PHANTOMS, INC.

VirtualDose™

A product of Virtual Phantoms, Inc.

Worldwide Users



31.5Million+ Dose Calculations Per Year

Outline of the presentation

Anatomical Modeling Tool

Dose Reporting Tool

VirtualDose

Organ Segmentation Tool

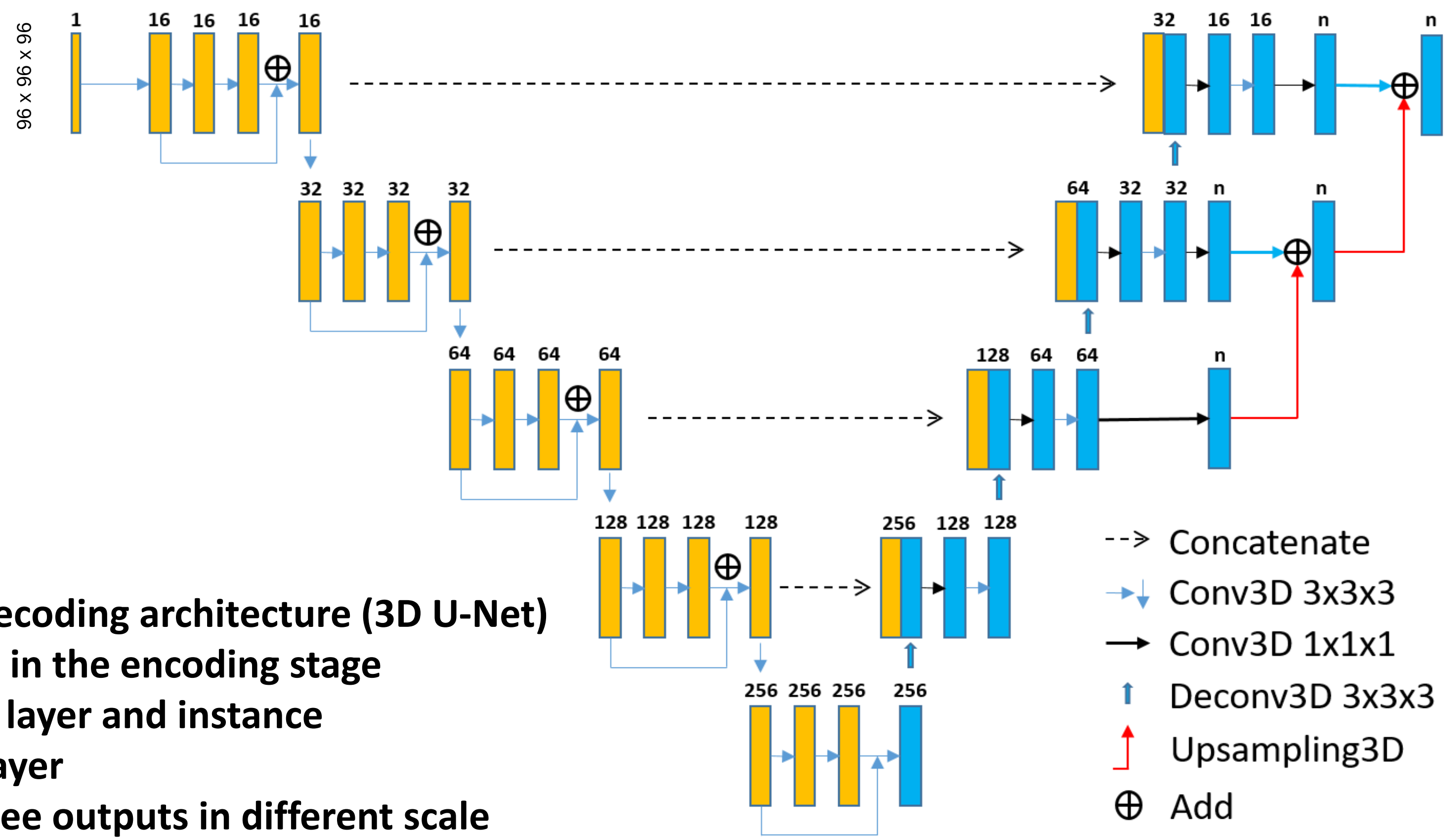
Deep Viewer

Dose Computing Tool

ARCHER

Moving towards Patient-Specific Phantoms - DL-based Auto Multi-organ Segmentation

Network architecture [1] :



Features:

- **Encoding and decoding architecture (3D U-Net)**
- **Res-net module in the encoding stage**
- **Spatial dropout layer and instance normalization layer**
- **Merging the three outputs in different scale and getting the final segmentation results**

[1] O. Ronneberger, P. Fischer, and T. Brox, "U-net: Convolutional networks for biomedical image segmentation," in *International Conference on Medical image computing and computer-assisted intervention*, 2015: Springer, pp. 234-241.

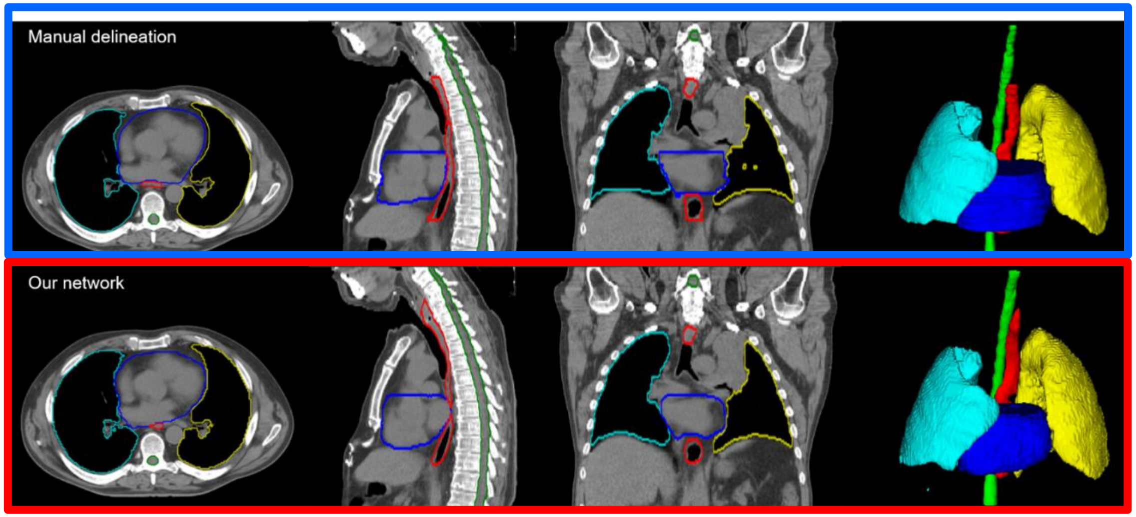
Dataset 1: Lung CT Segmentation Challenge 2017 (LCTSC) [2]

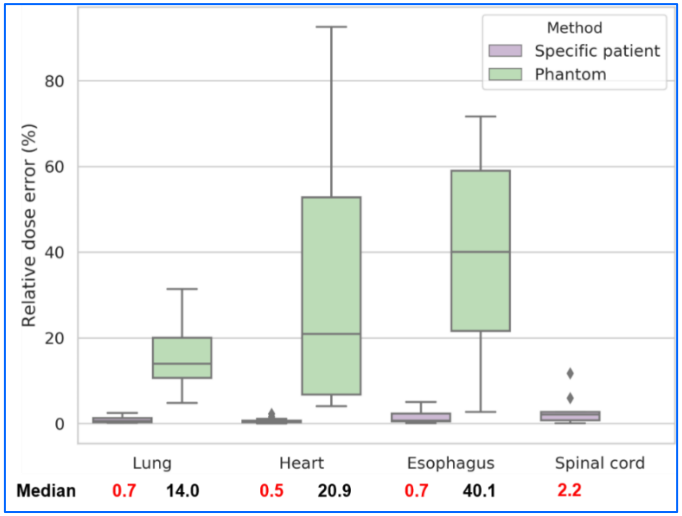
[2] Yang Jinzhong, et al. Data from Lung CT Segmentation Challenge (2017). The Cancer Imaging Archive.

- **Training and validation set:** 48 patients
- **Testing set:** 12 patients
- **Loss function:** weighted dice similarity
- **5 segmented organs:** left lung (yellow), right lung (cyan), heart (blue), spinal cord (green), and esophagus (red)

Dice similarity coefficient (mean ± standard deviation)

Methods	Left lung	Right lung	Heart	Esophagus	Spinal cord
Interrater variability	0.96±0.02	0.96±0.02	0.93±0.02	0.82±0.04	0.86±0.04
1	0.97±0.02	0.97±0.02	0.93±0.02	0.72±0.10	0.88±0.04
2	0.98±0.01	0.97±0.02	0.92±0.02	0.64±0.20	0.89±0.04
3	0.98±0.02	0.97±0.02	0.91±0.02	0.71±0.12	0.87±0.11
4	0.97±0.01	0.97±0.02	0.90±0.03	0.64±0.11	0.88±0.05
5	0.96±0.03	0.95±0.05	0.92±0.02	0.61±0.11	0.85±0.04
6	0.96±0.01	0.96±0.02	0.90±0.02	0.58±0.11	0.87±0.02
7	0.95±0.03	0.96±0.02	0.85±0.04	0.55±0.20	0.83±0.08
Ours	**0.96±0.01**	**0.96±0.02**	**0.93±0.02**	**0.73±0.10**	**0.88±0.04**



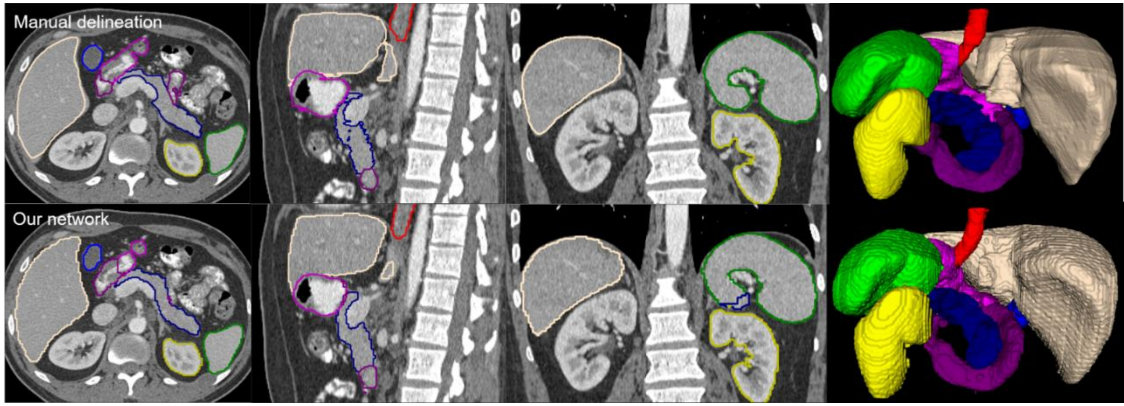


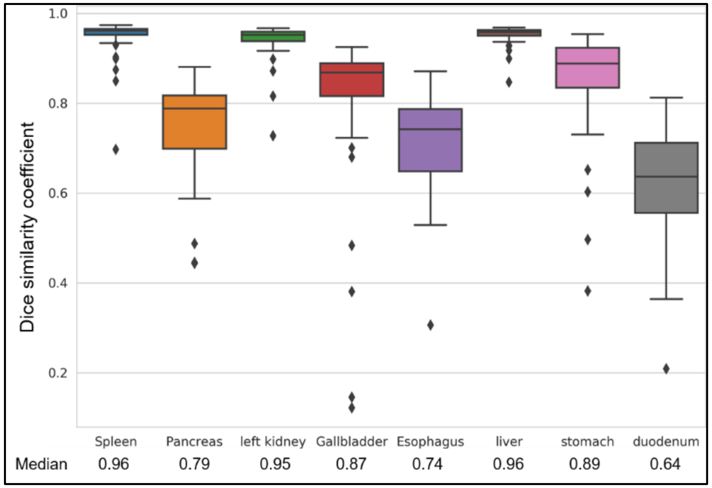
Peng Z, Fang X, Shan H, Liu T, Pei X, Yan P, Wang G, Liu B, Kalra M, Xu XG. Multi-Organ Segmentation of CT Images Using Deep-Learning for Instant and Patient-Specific Dose Reporting. AAPM, San Antonio, TX, July 14 – 18, 2019.

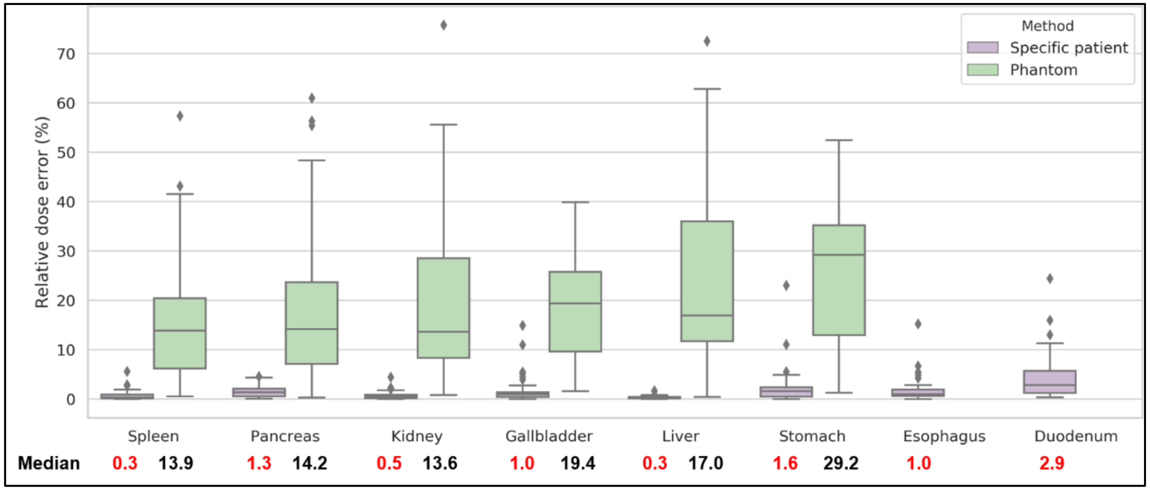
Dataset 2：The Cancer Image Archive (TCIA) Pancreas-CT [3]

[3] Gibson E, et al. Automatic multi-organ segmentation on abdominal CT with dense v-networks. IEEE Transactions on Medical Imaging, 2018.

Total patients: 43
5 cross-validation: 8, 8, 9, 9, 9
Loss function: weighted dice similarity coefficient
8 segmented organs: spleen (green), pancreas (navy), left kidney (yellow), gallbladder (blue), esophagus (red), liver (bisque), stomach (magenta), and duodenum (purple)

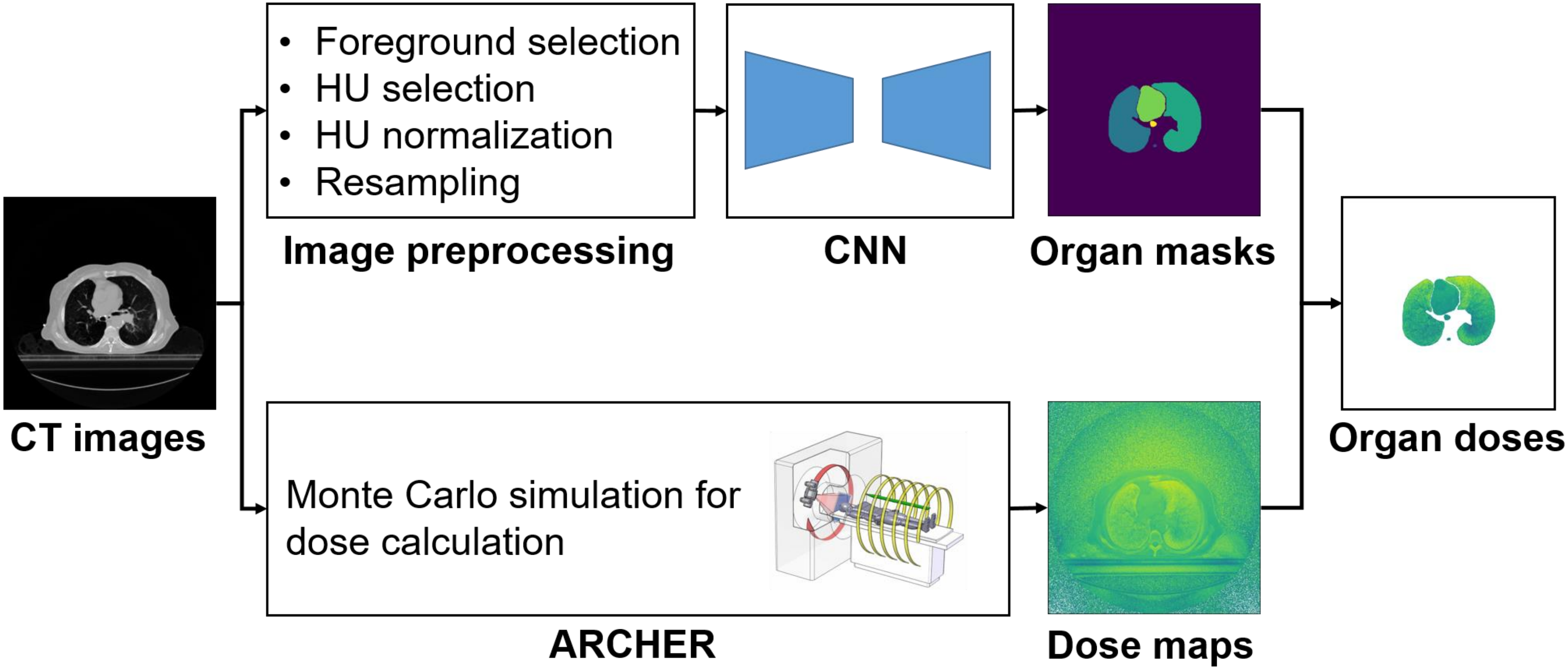




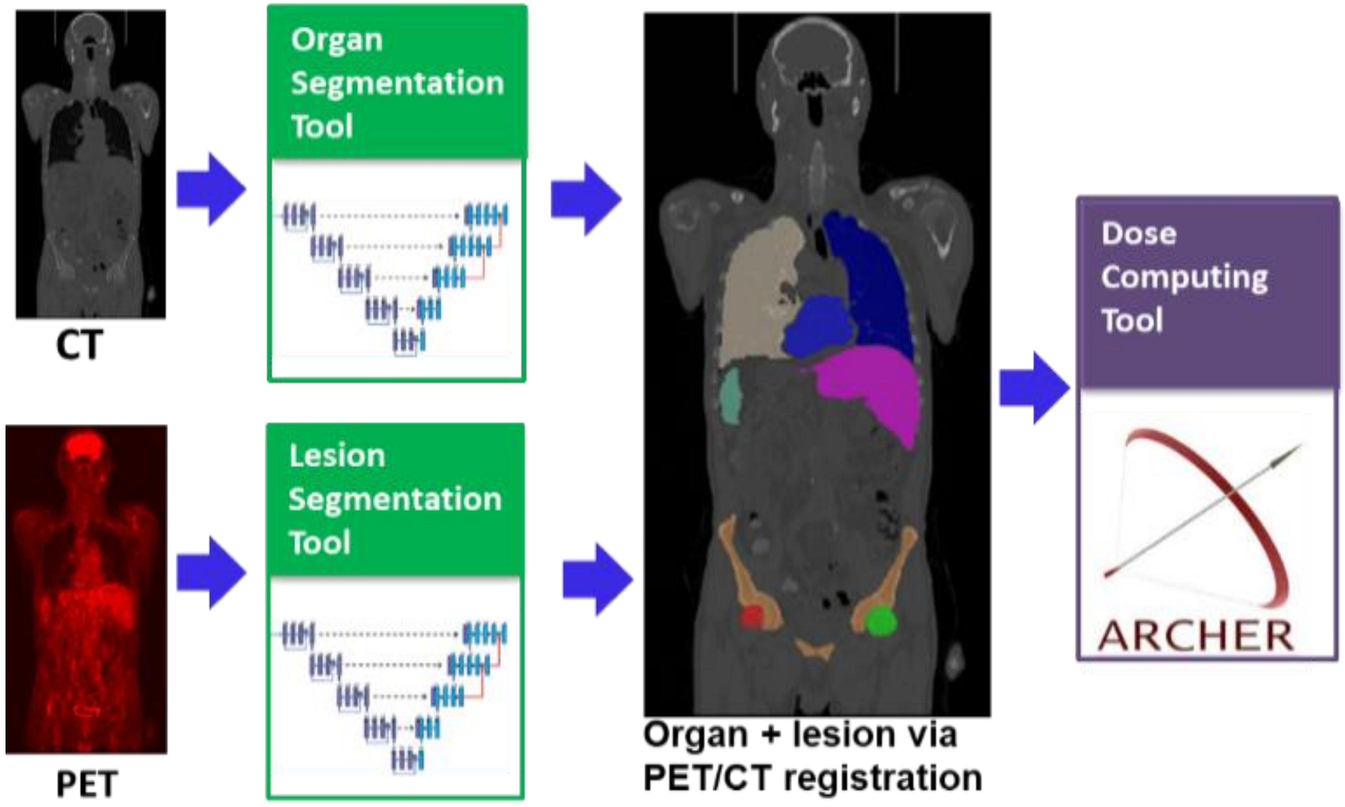


Peng Z, Fang X, Shan H, Liu T, Pei X, Yan P, Wang G, Liu B, Kalra M, Xu XG. Multi-Organ Segmentation of CT Images Using Deep-Learning for Instant and Patient-Specific Dose Reporting. AAPM, San Antonio, TX, July 14 – 18, 2019.

Method: The overall flowchart for creating patient-specific phantoms (CT)



Can also be done for PET/CT patient-specific phantoms



Segmentation Testing for the DeepViewer Tool

- **Can perform more than 40 organs and tissues**
- **Whole body in 3-5 minutes**

Organs	Dice
Skin	0.99
Brain	0.98
Lung	0.98
Liver	0.97
Spleen	0.95
Bladder	0.95
Cerebellum	0.95
Kidney	0.95

Organs	Dice
Brainstem	0.94
Femoral Head	0.93
Pelvis	0.93
Heart	0.93
Mandible	0.93
Trachea	0.92
Spinal Cord	0.92
Eye Ball	0.9

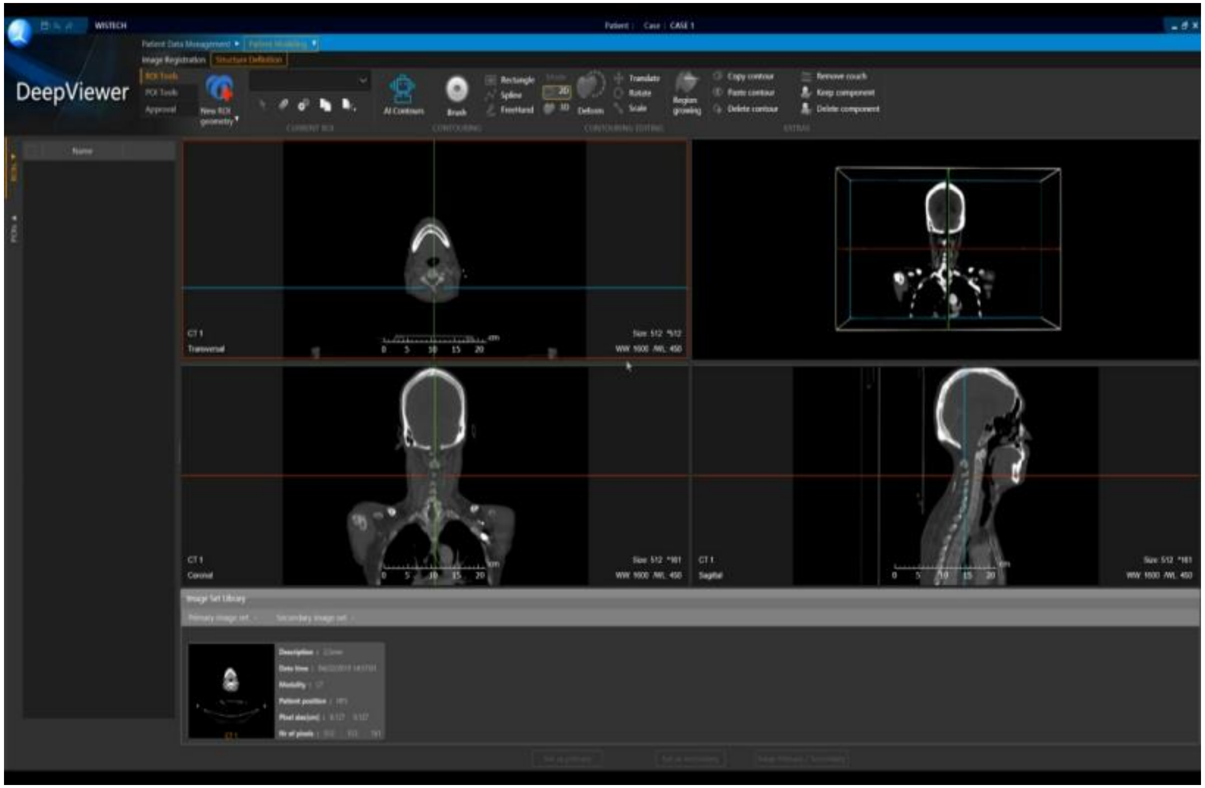
Organs	Dice
Stomach	0.88
Temporal Lobe	0.88
Parotid	0.86
Esophagus	0.86
Pancreas	0.86
Lens	0.85
Thyroid	0.85
Bowel	0.85

Organs	Dice
Larynx	0.85
Rectum	0.84
Oral Cavity	0.83
Breast	0.81
Optic Nerve	0.78
Pituitary	0.76
Optic Chiasm	0.75
Cochlea	0.75

Software Tool for Automatic Target and OAR Contouring in Radiotherapy

慧软科技 WISDOM TECH

DeepViewer



3D visualization

- **Support head/neck, chest, abdominal tumor treatment planning**
- **40+ OARs**
- **It takes 3-5 min to complete**
- **Acceptance rate 95% or better**

Outline of the presentation

Anatomical Modeling Tool

Dose Reporting Tool

VirtualDose

Organ Segmentation Tool

Deep Viewer

Dose Computing Tool

ARCHER

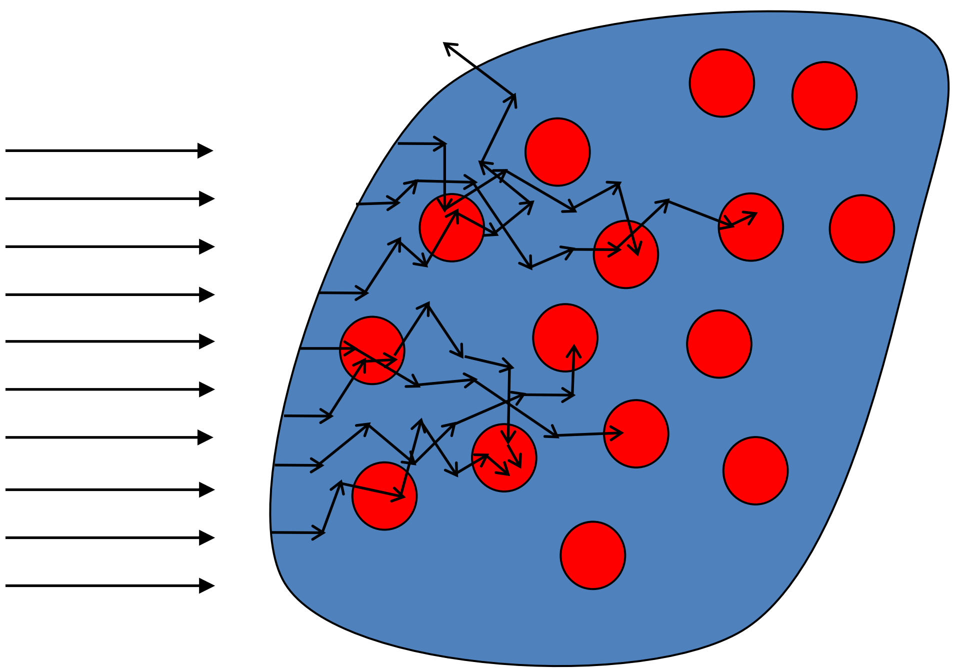
Monte Carlo Methods Ideal for Radiation Transport Simulations, but *Used to be Extremely Slow*

Boltzmann Transport Equation can be solved by MC methods

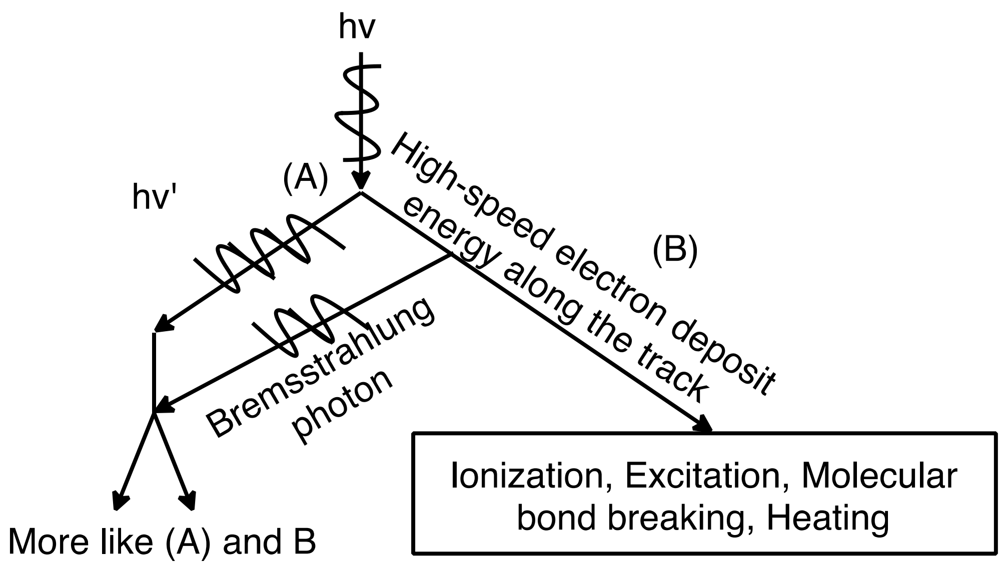
$$\frac{1}{\mathrm{v}}\frac{\partial}{\partial t}\psi(\vec{r},\hat{\Omega},E,t)+\hat{\Omega}\cdot\vec{\nabla}\psi(\vec{r},\hat{\Omega},E,t)+\Sigma_t(\vec{r},E)\psi(\vec{r},\hat{\Omega},E,t)$$

$$=\int dE'\int d\Omega'\Sigma_s(\vec{r},E'\rightarrow E,\hat{\Omega}'\cdot\hat{\Omega})\psi(\vec{r},\hat{\Omega}',E',t)+S(\vec{r},\hat{\Omega},E,t)$$

A Statistical Experiment



Introduction: Dose Calculation and Monte Carlo Methods

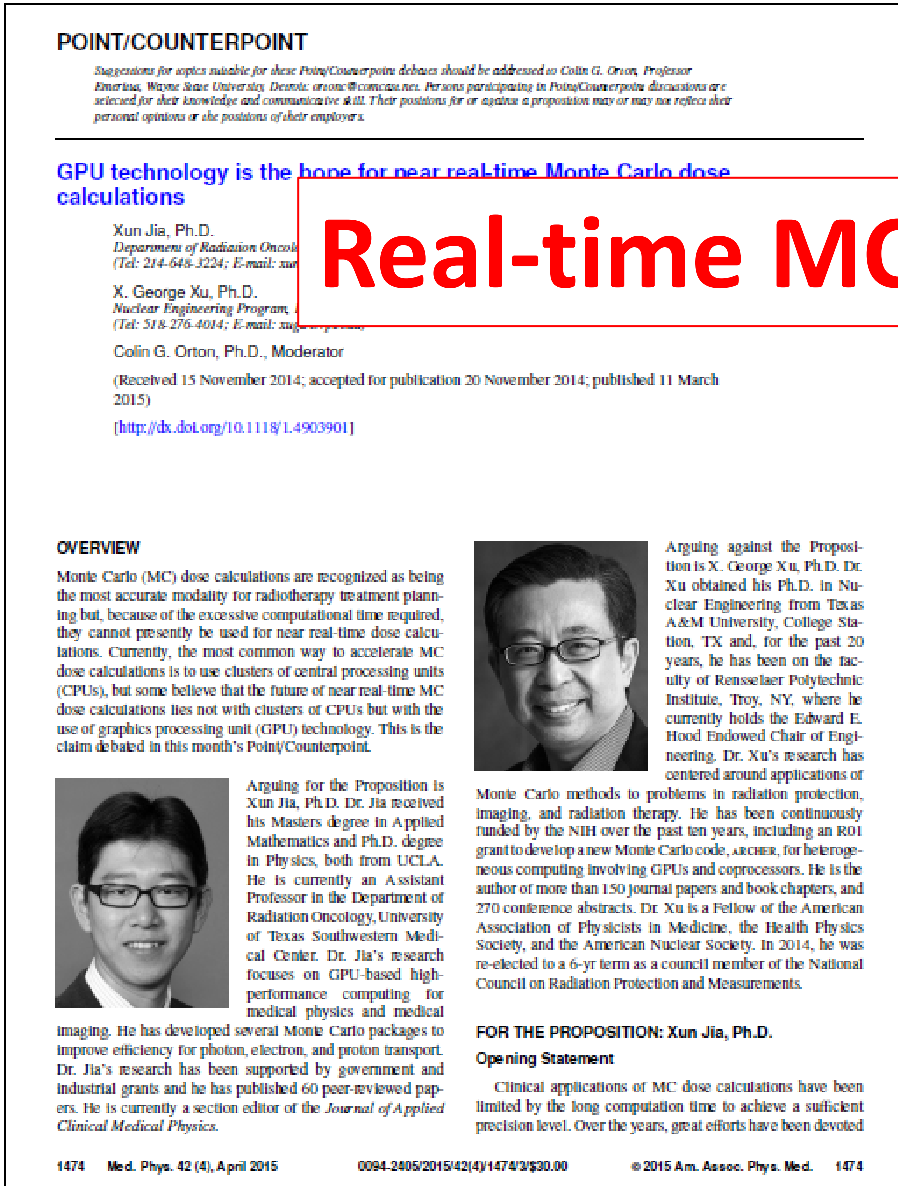


- Dose: energy imparted to matter via ionization and excitation per unit mass
- Deterministic methods subject to non-trivial errors by approximating electron transport in water
- Monte Carlo particle transport is the ***gold standard***
- But lengthy computation time is the main bottleneck of MC applications for clinical settings

The ARCHER Project

- ARCHER (Accelerated Radiation-transport Computations in Heterogeneous EnviRonments)
  - **Initiated in 2009**
  - **Goals:**
    1. To understand heterogeneous computing architecture and programming models
    2. To test code performance on GPUs and MICs
    3. To develop functional Monte Carlo codes that take full advantage of CPUs, GPUs and MICs

Solution: ARCHER – A GPU-based Monte Carlo Code



POINT/COUNTERPOINT

Suggestions for topics suitable for these Point/Counterpoint debates should be addressed to Colin G. Orton, Professor Emeritus, Wayne State University, Detroit: ortonc@comcast.net. Persons participating in Point/Counterpoint discussions are selected for their knowledge and communicative skill. Their positions for or against a proposition may or may not reflect their personal opinions or the positions of their employers.

GPU technology is the hope for near real-time Monte Carlo dose calculations

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(Tel: 214-648-3224; E-mail: ...

X. George Xu, Ph.D.
Nuclear Engineering Program, ...
(Tel: 518-276-4014; E-mail: ...

Colin G. Orton, Ph.D., Moderator

(Received 15 November 2014; accepted for publication 20 November 2014; published 11 March 2015)

[http://dx.doi.org/10.1118/1.4903901]

OVERVIEW

Monte Carlo (MC) dose calculations are recognized as being the most accurate modality for radiotherapy treatment planning but, because of the excessive computational time required, they cannot presently be used for near real-time dose calculations. Currently, the most common way to accelerate MC dose calculations is to use clusters of central processing units (CPUs), but some believe that the future of near real-time MC dose calculations lies not with clusters of CPUs but with the use of graphics processing unit (GPU) technology. This is the claim debated in this month's Point/Counterpoint.

Arguing for the Proposition is Xun Jia, Ph.D. Dr. Jia received his Masters degree in Applied Mathematics and Ph.D. degree in Physics, both from UCLA. He is currently an Assistant Professor in the Department of Radiation Oncology, University of Texas Southwestern Medical Center. Dr. Jia's research focuses on GPU-based high-performance computing for medical physics and medical imaging. He has developed several Monte Carlo packages to improve efficiency for photon, electron, and proton transport. Dr. Jia's research has been supported by government and industrial grants and he has published 60 peer-reviewed papers. He is currently a section editor of the *Journal of Applied Clinical Medical Physics*.

Arguing against the Proposition is X. George Xu, Ph.D. Dr. Xu obtained his Ph.D. in Nuclear Engineering from Texas A&M University, College Station, TX and, for the past 20 years, he has been on the faculty of Rensselaer Polytechnic Institute, Troy, NY, where he currently holds the Edward E. Hood Endowed Chair of Engineering. Dr. Xu's research has centered around applications of Monte Carlo methods to problems in radiation protection, imaging, and radiation therapy. He has been continuously funded by the NIH over the past ten years, including an R01 grant to develop a new Monte Carlo code, ARCHER, for heterogeneous computing involving GPUs and coprocessors. He is the author of more than 150 journal papers and book chapters, and 270 conference abstracts. Dr. Xu is a Fellow of the American Association of Physicists in Medicine, the Health Physics Society, and the American Nuclear Society. In 2014, he was re-elected to a 6-yr term as a council member of the National Council on Radiation Protection and Measurements.

FOR THE PROPOSITION: Xun Jia, Ph.D.

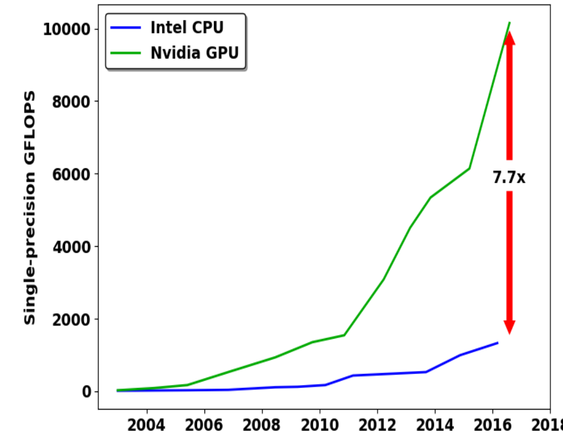
Opening Statement

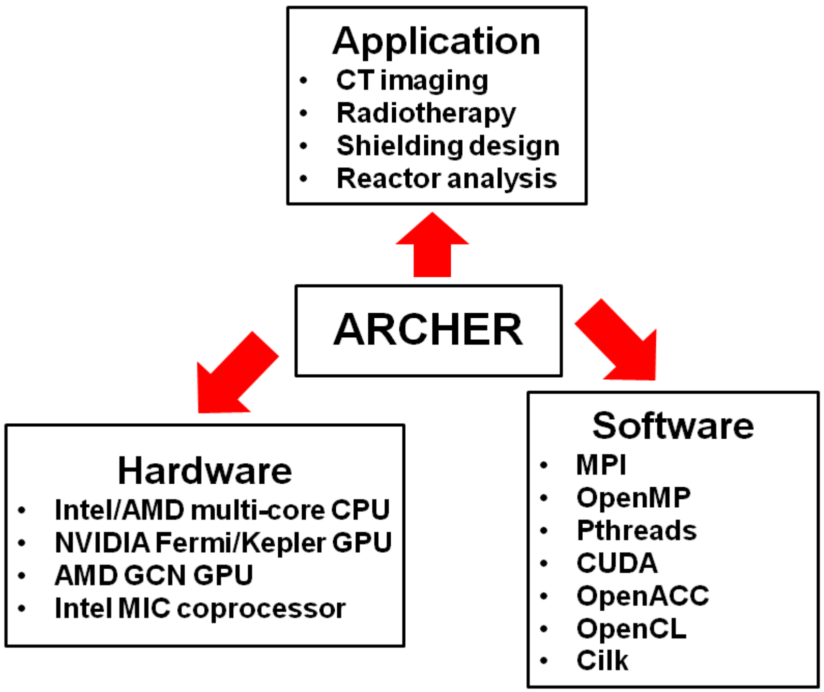
Clinical applications of MC dose calculations have been limited by the long computation time to achieve a sufficient precision level. Over the years, great efforts have been devoted

Real-time MC?

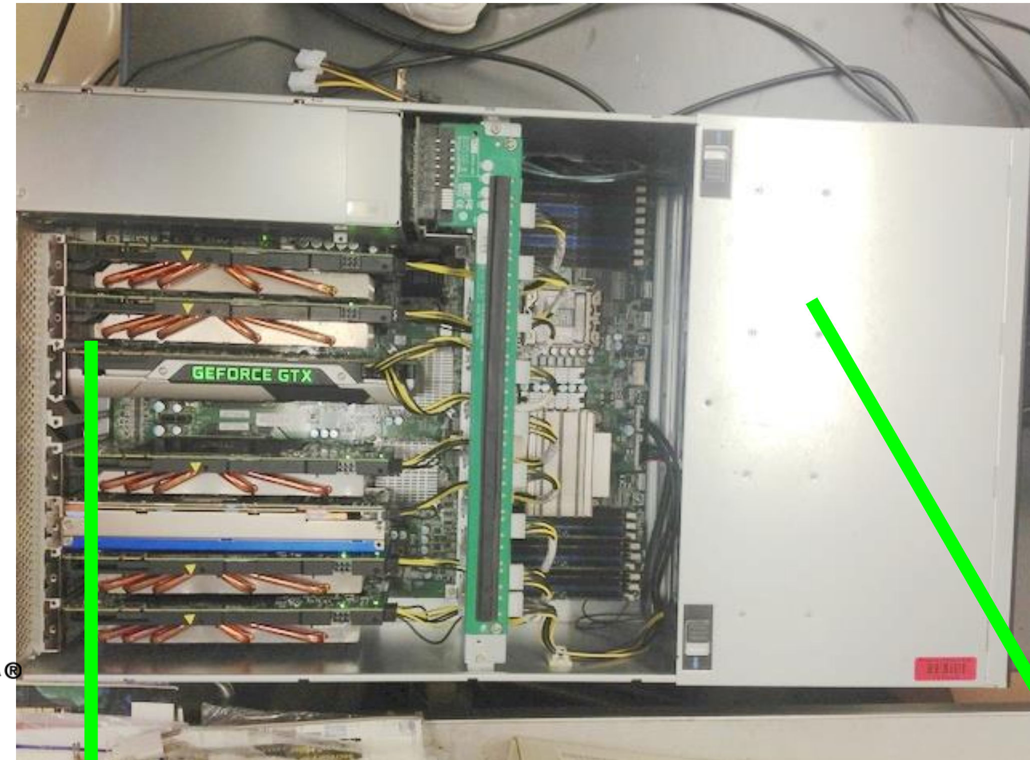
Med. Phys. 42 (4), April 2015

GPU is more powerful than CPU





Desk-Top CPU/GPU Hardware @ $10k



Intel CPU

Multiple Nvidia GPU cards

[1]

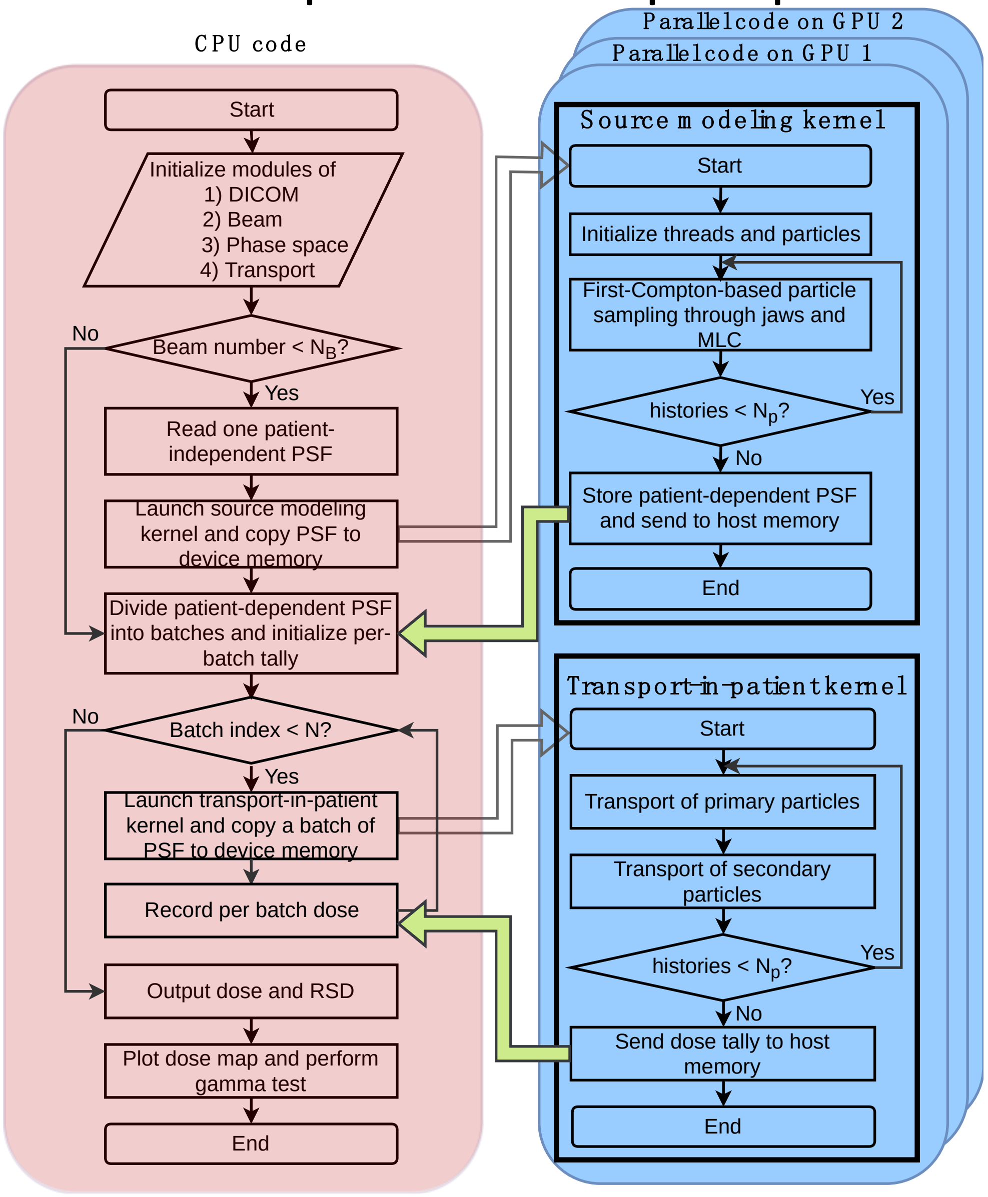
ARCHER Software Development

- Workflow of synchronized source model-particle transport process

  – Two code variants

  ➢ $ARCHER_{CPU}$: supports multi-threaded parallelization

  ➢ $ARCHER_{GPU}$: supports multi-GPUs parallelization

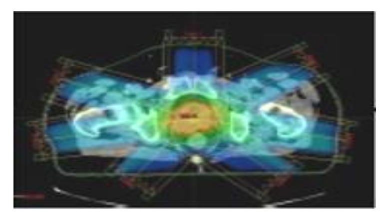


Introduction: External-Beam Radiotherapy

- 1.7 million new cancer cases in the U.S in 2017[1]
- 52% cancer patients receive external photon beam radiotherapy
- Radiation Therapy aims to maximizes the dose to the tumor, while minimizing the dose to adjacent health tissues

Obtain patient CT image

CT virtual simulation



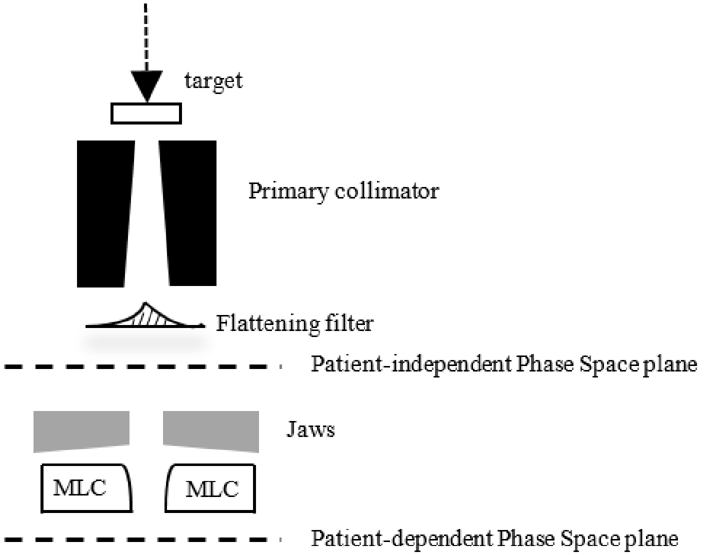
Dose Calculation & plan optimization

Treatment verification and delivery

- The accuracy of dose calculations is crucial to treatment planning and dose delivery
  - Accuracy of the source term modeling
  - Accuracy of the dose calculation methods

[1] Siegiel, R., K. D. Miller, and A. Jemal. CA Cancer J Clin 67 (2017): 7-30.

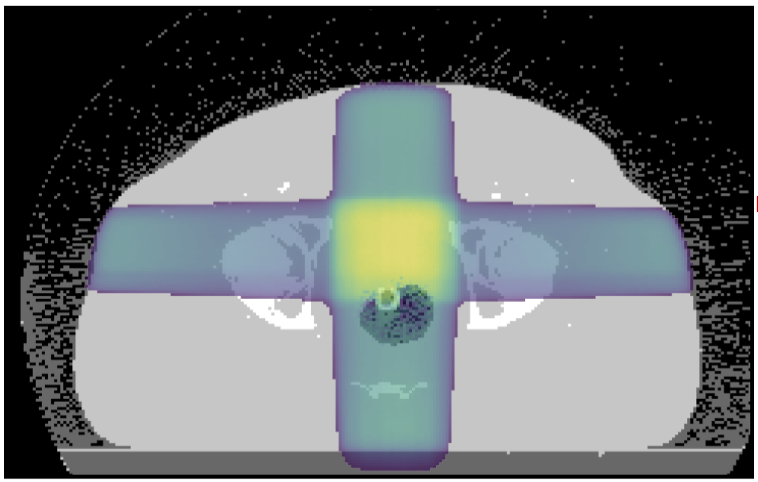
Virtual Source Modeling



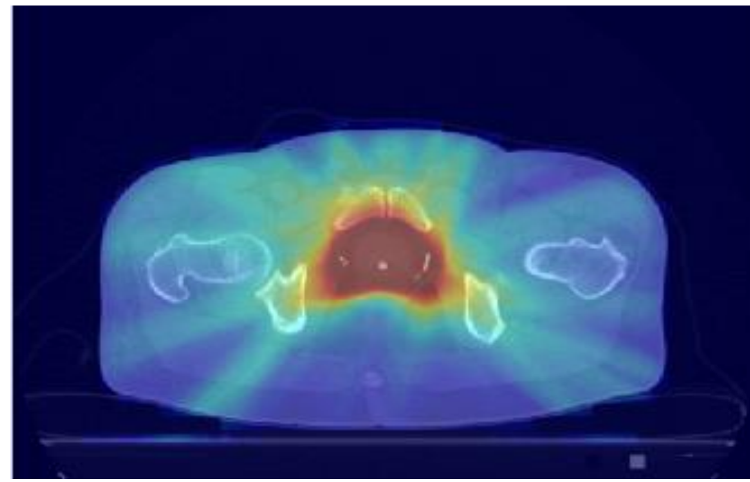
- Phase space source
  - Phase space particles: a collection of representative pseudo-particles emerging from a radiotherapy source along with their properties (x, y, z, u, v, w, E, wt)
  - can be categorized as
    - ➢ Patient-independent phase space: could be utilized repeatedly
    - ➢ Patient-dependent phase space: specific to each plan and beam

Results: ARCHER for External-Beam Therapy (Tomotherapy, IMRT and VMAT) [1-5]

Step and Shoot IMRT



VMAT



(1) Liu T. Development of ARCHER - a parallel Monte Carlo radiation transport code -- for X-ray CT dose calculations using GPU and coprocessor technologies, Ph.D. Dissertation, Rensselaer Polytechnic Institute (2014).

(2) Su L. Development and Application of a GPU-Based Fast Electron-Photon Coupled Monte Carlo Code for Radiation Therapy, Ph.D. Dissertation, Rensselaer Polytechnic Institute (2014).

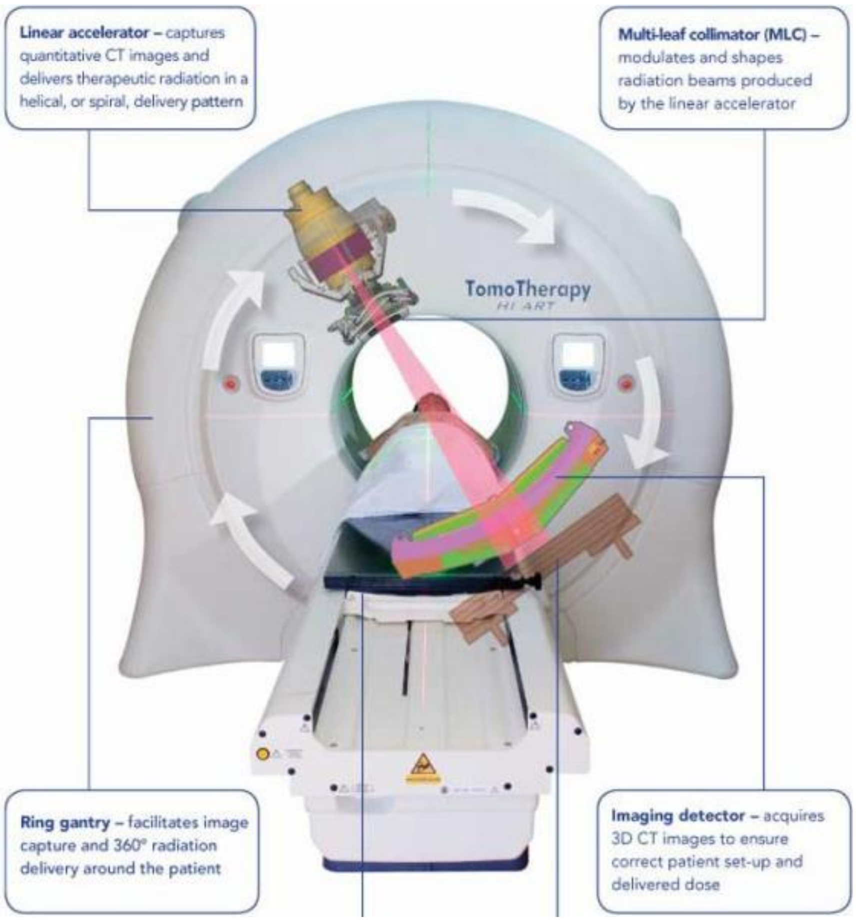
(3) Lin H. GPU-based Monte Carlo Source Modeling and Simulation for Radiation Therapy involving Varian Truebeam Linac. , Ph.D. Dissertation, Rensselaer Polytechnic Institute (2018).

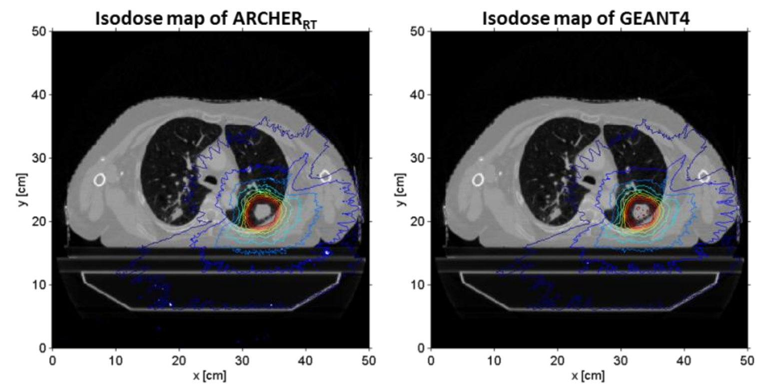
(4) Su L, Yang YM, Bednarz B, Sterpin E, Du X, Liu T, Ji W, Xu XG. $ARCHER_{RT}$ — A Photon-Electron Coupled Monte Carlo Dose Computing Engine for GPU: Software Development of and Application to Helical Tomotherapy. Med Phys. 41:071709 (2014).

(5) Adam DP*, Liu T, Caracappa PF, Bednarz BP, Xu XG. New capabilities of the Monte Carlo dose engine ARCHER-RT: clinical validation of the Varian TrueBeam machine for VMAT external beam radiotherapy. Med Phys 2537-2549 (2020).

Results: Tomotherapy

Su L, Yang YM, Bednarz, Edmond Sterpin, Du X, Liu T, Ji W, Xu XG. ARCHERRT — A Photon-Electron Coupled Monte Carlo Dose Computing Engine for GPU: Software Development of and Application to Helical Tomotherapy**. <u>Med Phys</u>** (2014).





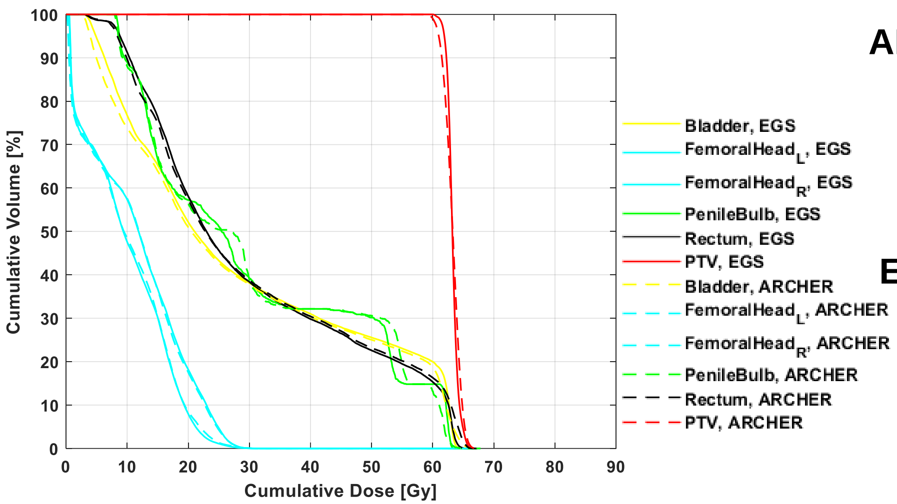
Statistical error in PTV ~1%

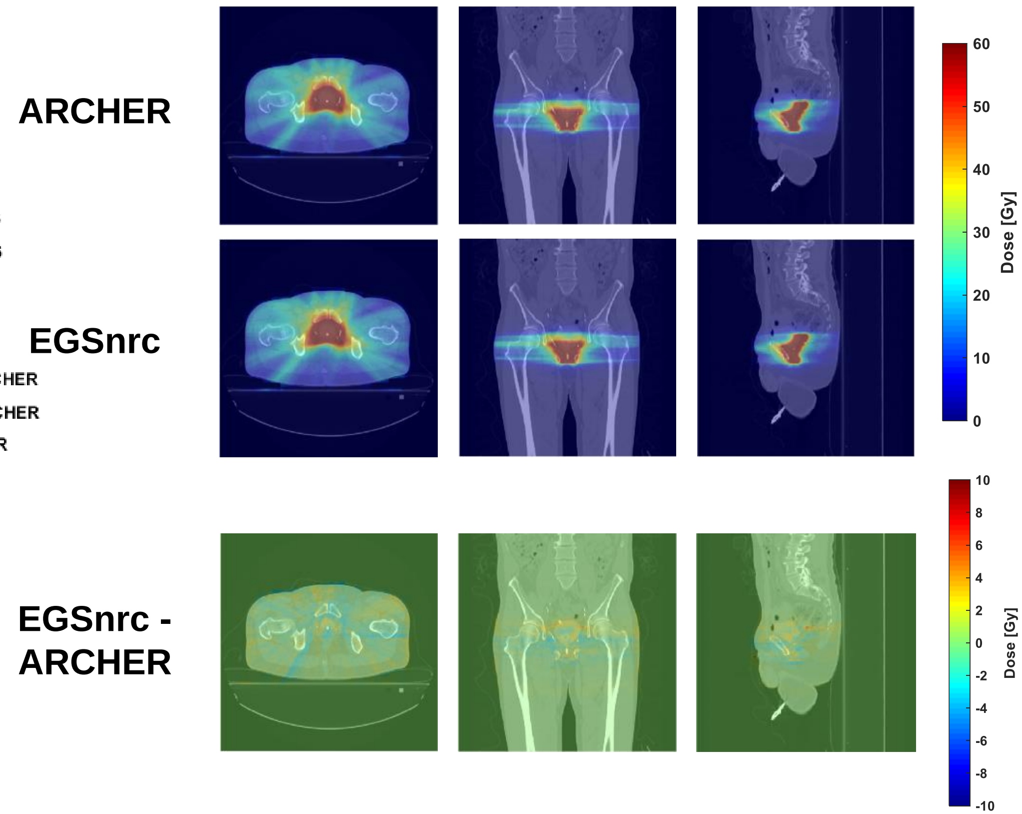
2%/2mm Gamma test pass rate: 98.5%

GPU computing time ~ 1 sec,

reducing from GEANT4 <u>~ 500 CPU hours</u>

Results: Clinical VMAT (prostate case)





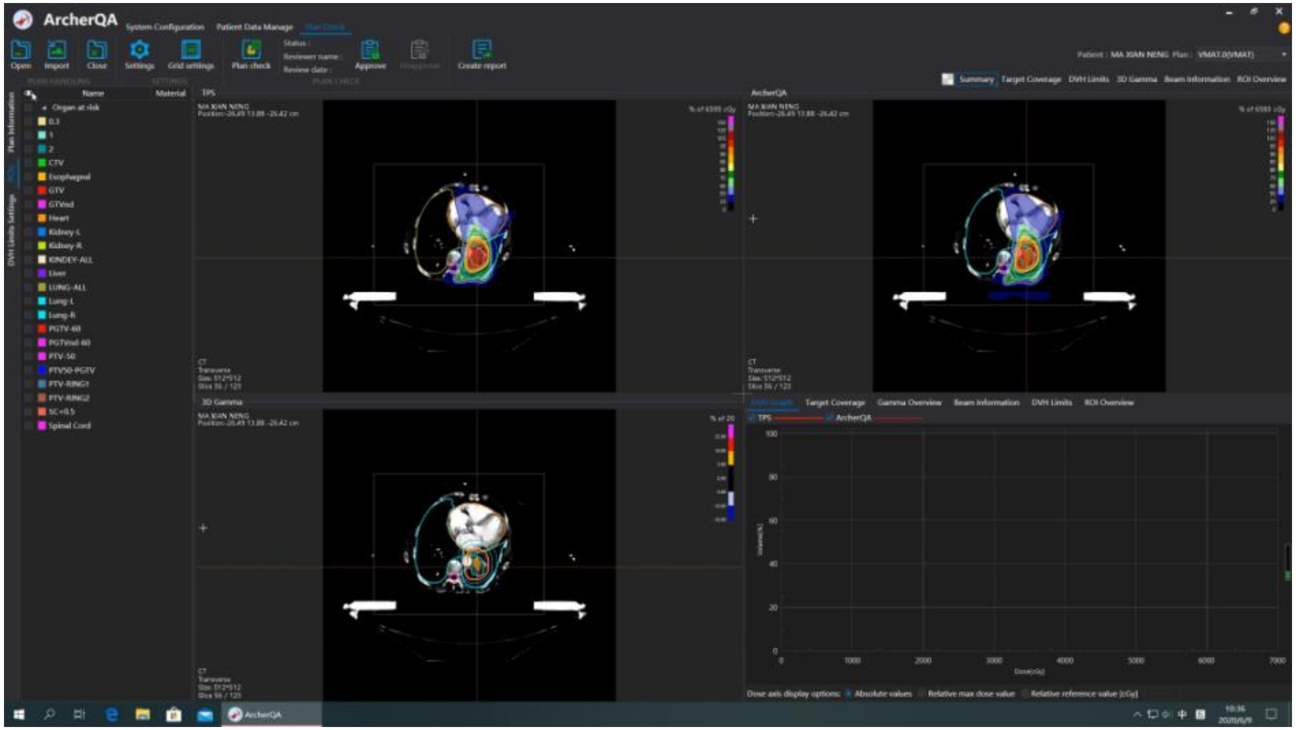
- Gamma pass rates:
  - 3%/3mm: 99.71%

- ❑ **ARCHER (NVIDIA 1080Ti GPU)** ➡ **48 seconds**
  - ❑ Patient transport
  - ❑ Source modeling (linac)
- ❑ **EGSnrc (120-node cluster Intel Xeon E5335 CPUs)** ➡ **24 hours**

Software Tool for 3D Independent Dose-check (verification of TPS results)

ArcherQA

1. GPU-accelerated Monte Carlo dose engine
2. Data analyze tools, such as 2D and 3D Gamma Test and DVHs
3. TPS and Machine Check
4. Friendly user interfaces, easy to commission and setup



Archer QA GUI

Treatment Planning System (TPS), DeepPlan

- Photons, electrons, protons
- Different dose algorithms including GPU-based Monte Carlo
- Integrated with auto contouring and registration

Summary

1. **Personalized patient organ-dose always needed for radiation treatment planning**

2. **The workflow greatly facilitated by:**
   - ✓ **AI –based automatic segmentation tools are well tested**
   - ✓ **Real-time MC computing provides RT QA solutions**

3. **A paradigm change from "population averaged" Reference Man to "personalized organ doses" is feasible**

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VirtualDose™ CT
A product of Virtual Phantoms, Inc.

DeepViewer

ARCHER

DeePPLAN